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GEOLOGICAL FACTORS IN THE VALUATION OF MINES.*

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INTRODUCTION.

SOME years ago, the manager of a mining company, with which I was associated, had a habit of annoying his geological staff by making uncomplimentary distinctions between what he called "real ore" and "geological ore." By the first term, he meant, of course, ore that could be estimated by rule-of-thumb engineering methods with the precision that passes for certainty in some quarters, in contrast to ore that required a higher order of imagination to recognize. After some reflection, I am now willing to accept the distinction as a valid one, but with the comforting observation that in most successful mines there have been periods when the value that could properly be attached to "geological ore," as just defined, considerably exceeded that calculated from strictly defined ore reserves.

Among the many factors that determine future profits and that provide the means of estimating present value, the one that above all others gives mining ventures their own particular quality is *ore supply*. On it, the whole enterprise depends; and when the ore is exhausted, the period of profits or of hope of profits is over.

Mining, as investments go, is usually regarded as a more speculative undertaking than the average industry, but once the existence of an adequate ore-body is established, the dangers and difficulties in modern practice are surely not enough to put it in

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an especially high risk category. Engineering and technical problems in mining and metallurgy may at times be of unconventional sort and require more than ordinary ingenuity in their solution, but, given the raw material in proper quantity and grade, either in the ground or in a bin, one can confidently expect, these days, that some successful way will be found to recover the metal. Indeed, apart from questions involving ore supply, the hazards that have to be faced in mining are merely those that plague industrial enterprises in general. Wage scales, cost of materials, and taxes; fluctuations in output and changing needs of consumers; metal prices; all introduce variables that may be more difficult to estimate and predict than the vagaries of ore deposits. But these uncertainties are by no means unique to mining.

Differences in the degree of probability with which the quantity and composition of the ore in a deposit can be appraised create great contrasts between various mining ventures from the standpoint of financial risk. In some, where all the available orebody can be easily drilled or tested by other reliable means, the danger of loss through lack of ore can be practically eliminated except with regard to the initial expenditure on exploration. At the same time, however, the prospects for something better are likewise eliminated, or at least are very much reduced, and the enterprise loses much of its appeal to those who hope for more spectacular benefits. At the other extreme are mines on deposits in which, for one reason or another, development cannot be pushed far ahead of actual operations, where tonnage or grade cannot be precisely measured, and where expectation of ore depends largely upon geologic evidence.

These contrasts result directly from fundamental differences in the geologic nature of the ore deposits themselves; but before entering upon a discussion of the particular characteristics that determine the category of risk to which the mining enterprises dependent on them belong, the conventional procedure employed in valuation will be reviewed briefly to direct attention to the specific terms in which these geological considerations find formal expression.

Conventional Valuation Procedure.—The value of a mine depends solely on the profits that can be made from it. The process of valuation is an appraisal of the amount of these profits and of the rate at which they will be received, and their reduction to present value. To accomplish this, the following items must be measured, estimated, designed, or assumed:

(1) Available ore supply;
(2) Cost of producing the metallic product;
(3) Mining and metallurgical recovery;
(4) Rate of production;
(5) Selling price of the metal or metallic product; and
(6) Interest rates.

No one of these factors is entirely independent. Some are capable of fairly exact determination. Others are largely matters of judgment, but in such cases the degree to which results are influenced by specific assumptions should at least be apparent.

From data of this sort, present value is usually calculated by the well known Hoskold formula,[1] which has been widely used throughout the English-speaking mining world since the clear and concise statement of the sound reasoning that underlies it was made by our distinguished fellow member, Herbert Hoover.[2] The formula, and the tables based on it,[3] simply indicate the price that could be paid for a mining property with the expectation that the dividends received during the life of the operations will be adequate both for interest at the desired rate and for amortization.

The interest rate employed for the accumulation of the sinking fund by which the capital is amortized is usually taken as the current return on bonds of the best grade or on savings bank accounts. (Not long ago, four per cent was commonly assumed!) The rate of interest expected from the investment, after provision

[1] Hoskold, H. D.: Engineers' Valuing Assistant. Longmans, Green and Co., London, 1877.

[2] Hoover, Herbert: Principles of Mining. Hill Publishing Co., N. Y. 1909. (Chapter V.)

[3] Inwood's Tables of Interest and Mortality. Crosby, Lockwood and Son, pp. 186–204, 32d edition, London, 1924. (First edition, 1811.)

for the sinking fund has been made, obviously should be higher than the security rate, and it, of course, increases directly with the degree of risk that is involved.[4]

In the valuation of profits expected from *known ore reserves*, as measured in good practice, no higher interest rate is warranted, in my judgment, than that currently obtained on investments in comparably situated industries, involving business risks of a similar sort. For this sharply defined portion of the life of a competently operated mine, during which dangers arising from vagaries of ore-bodies are at a minimum, five to seven per cent (after provision for amortization) would be a fair return, if no abnormal external conditions exist, such as geographical remoteness or political and social complexities that would handicap any enterprise undertaken for profit. Higher rates of interest obviously should be used in calculating present value of profits anticipated from ore still to be developed or in discounting such values for whatever period of deferment is indicated. Selection of a proper rate is essentially an expression of opinion concerning the hazards of the particular enterprise. It depends upon the synthesis of too many variables, however, to be precisely calculated and to a large extent it is necessarily a matter of judgment.

In general, I am inclined to think that mining engineers and geologists from habitual caution in appraising prospects for ore beyond the limits of known reserves are apt to use interest rates that are too high in formal valuations of successful mining properties, and, consequently, tend to make over-conservative estimates of present value. The public, on the other hand, usually goes to the other extreme, particularly in prices paid for mines in an early stage of exploration, when the restraining influence of professional advice would be decidedly beneficial; but it is also worth noting that those who hold with some authorities that interest at

[4] Good discussion of principles of mine valuation may be found in the following publications: Graton, L. C.: Federal taxation of mines. Mining and Metallurgy, No. 155, Nov., 1919, A. I. M. E. Hoover, Theodore J.: The Economics of Mining. Stanford Univ. Press. 1933. Pp. 21–204. Truscott, S. J.: Mine Economics. Mining Publications, Ltd. London. 1937. Ch. 10–12.

10 to 20 per cent is a requirement for mining investments are not likely to have opportunity to acquire shares in well managed dividend paying companies, except under panic conditions.

The investment rate, as defined by the Hoskold formula, should not, of course, be confused with the dividend rate. The ratio of the annual dividend to the present value is necessarily large in a short-lived enterprise, even though the risk expressed by the investment rate might be small; whereas in a more speculative but long-continued operation the dividend rate, expressed as a percentage of the present value, could be much lower and yet provide interest at the higher rate that would be warranted. Incidentally, it is perhaps worth noting that the currently popular market valuation of many mines at "ten times earnings" requires a life of 15 years to return the principal and pay interest even at the moderate rate of 5 per cent and sinking fund rate of 4 per cent; or 18 years at 6 and 4 per cent; or 22 years at 7 per cent and 4 per cent. In the absence of ore reserves adequate for the life necessary to justify this ratio, the extent to which such off-hand valuations depend upon expectation of additional or better ore should be recognized; and the extent to which this judgment depends upon evaluation of geologic evidence likewise should not be overlooked.

The gross quantity of metal that can be expected from a deposit is, of course, directly calculated from estimates of tonnage and grade of ore. Multiplied by the price per unit, its gross value is obtained. The cost of mining likewise depends to an important degree upon the form, grade, and distribution of the ore-bodies; the recovery of metals is influenced by the mineral composition and texture; and the rate of production and outlay for plant are determined very largely by the size of the deposit and the type of mining and treatment that it permits. Thus, each of these basic factors, as well as the interest rates previously discussed, involves geologic considerations that must be taken into account in any systematic valuation. In the following discussion, however, emphasis will be placed principally upon those characteristics of mineral deposits by which the primary and dominant factor—ore supply—can be appraised.

Measurable Ore Versus Prospective Ore.—In most discussions of mine valuation, attention is devoted chiefly to the procedure by which the profits to be derived from a thoroughly developed ore-body are estimated. The danger of loss from failure of this portion of the ore supply is reduced simply to the chances for error arising from such causes as short-sighted economies in exploration programs, neglect of geological realities in design of sampling and in the interpretation of assay returns, or incompetence or worse on the part of a technical staff. With professional skill and ethics at their best levels, these risks should be small, though, of course, a careful investor should not so assume until he had ascertained that those making such estimates were qualified in all respects for responsibility of the order imposed by the nature of the deposit and the enterprises dependent on it. With these conditions satisfied, the most serious risk peculiar to mining is reduced to ordinary dimensions, or nearly eliminated under most favorable circumstances, as far as the portion of the value is concerned that is derived from measurable ore reserves, blocked out in accordance with intelligent conventional standards.

If, however, it is apparent, as it is in most cases, that the property possesses prospects for ore still relatively untested beyond existing limits of development, ore supplies of other risk categories also have to be taken into account. Their tonnage and grade cannot be determined by routine engineering measurements, but some appraisal of their magnitude and possible metal content can usually be made by projection of known ore shoots to reasonable limits, by statistical studies, by structural correlations of various sorts, or by other lines of geologic evidence.

Obviously, attempts to express "geological ore" of this sort in precise terms need to be carefully qualified to avoid giving false impressions; but in some cases it may be permissible to estimate possible tonnages and metal content in round figures, based on clearly stated assumptions, and to reduce the indicated profits to a properly conservative present value by using the higher interest rates that would be commensurate with the risk that is involved.

Or, if an arbitrary value is attached to mere prospects for ore, the calculation might be reversed and some idea gained as to whether or not the quantity of ore needed to justify a stated figure was a reasonable expectation in terms of the geologic evidence.[5] Even though such estimates are not based on the usual conventional methods, they serve to reduce vaguely expressed hopes to finite dimensions which can be measured against the observed conditions, and discounted or strengthened accordingly.

In their initial stages of development, the value of most mining properties depends upon their prospects for ore rather than upon ore actually blocked out. A supply of assured ore adequate to return the cost of mine and milling plants is usually desired in good practice before expenditures for these purposes are made; but, even under these conditions, the chances for profits from ore still to be developed are generally appraised at a figure that gives the venture a substantial additional value, unless it is already a disappointment and the mill built merely to salvage the expenditures to date. In most successful mines, a certain operating equilibrium is eventually attained between measurable ore reserves and prospects for additional ore. The proper ratio between these two very real elements of value, however, as revealed by good practice, ranges between wide limits, for it depends largely on the type of deposit that is being exploited.

CLASSIFICATION OF ORE DEPOSITS ON BASIS OF ASSURANCE OF ORE SUPPLY.

The striking differences in the nature of the evidence on which estimates or appraisals of ore supply depend are of such vital concern to those who risk their funds in mining ventures that geologists may very properly be called upon to review their assemblage of facts and fancies about ore deposits and to express their opinions concerning the degree of confidence in the existence of ore that is justified in deposits of various types. As a step in this direction, an attempt is made on the following pages to classify deposits according to the assurance of ore supply that

[5] Hoover, H. C. Op. cit., p. 45.

they are ordinarily capable of providing with the amount of exploration that is customary in good current practice in active producing mines developed on them. With this object in mind, three major groups, as defined below, are set up, and the common types of ore deposits are assigned to them as nearly as possible by the features that determine the category of risk to which they belong, when appraised as sources of ore.

I. Plenemensurate ore-bodies—those capable of being fully measured and sampled at an early stage in the operations;
II. Partimensurate ore-bodies—those in which prospects for ore in addition to proved reserves remain a substantial element of value until the later stages of the life of the mines based on them;
III. Extramensurate ore-bodies—those difficult to explore and measure much in advance of mining, in which the value of prospects for ore based on geologic evidence exceeds the value based on proved reserves throughout most of the life of mines supported by them.

These headings, of course, merely designate successive parts of a gradation in which the various deposits are arranged as nearly as possible according to the ratio between assured ore supply and prospective ore (or "geologic ore") that is usually attained in them in good practice, when mining operations are in full swing. The rough classification given below does not conform strictly to genetic lines, for other considerations, some of which are only indirectly dependent on concepts of origin, must also be taken into account if deposits with similar qualities from a valuation standpoint are to be grouped together. Assignment of particular deposits to one or another of the major groups and to their place in the sequence is determined to a large extent by the following characteristics:

(1) Size, form and attitude of the deposit.
(2) Accessibility to exploration.
(3) Continuity or regularity in metal content.
(4) Persistence of the mineralization, and particularly of the metal-bearing phase, as revealed by mineral species, textures and alteration.
(5) Controls determined by structure and environment.

In the review of various deposits regarded in terms of ore supply, which makes up the bulk of the remaining part of this address, these features will be emphasized. Examples, for the most part, have been selected from districts or mines of major rank as metal producers, or from those that are fairly well known.

Classification of Ore Deposits according to Assurance of Ore Supply Afforded by Them.

I. PLENEMENSURATE DEPOSITS.

Mechanical concentrates not deeply buried by later formations.

Gold dredging gravels.
Sacramento Valley fields,* Cal.
Bulolo field, New Guinea.

Tin dredging gravels.
Malayan fields.

Flat-lying or gently inclined sedimentary ore bodies.

Sedimentary iron ores.
Luxembourg-Lorraine field.
Jurassic iron ores of England.

Sedimentary manganese ores.
Manganese ores of Trans-Caucasia.

Low grade ores or iron formations, locally enriched.
Mesabi iron range, Minn.

Residual ore deposits formed by weathering from present surface.

Lateritic iron ores.
Mayari and Moa fields, Cuba.

Bauxite ores.
Arkansas deposits.

Supergene ores formed from earlier sulphide mineralization, not buried by later deposits.

Oxidized ores above sulphide ore bodies of large horizontal section.
Silver-pacos ores of Cerro de Pasco, Peru.
Copper sulphate ores of Chuquicamata, Chile.
Ajo carbonate ores (now exhausted), Ariz.

Copper carbonate ores in flat-lying limestone beds, or on flat fractures.
Katanga, Belgian Congo.

Chalcocite-covellite disseminated ores of porphyry copper type.
Chino, New Mex.
Inspiration-Miami ore body, Ariz.
Ray, Ariz.

Concordant veins or lodes in bedded rocks, confined to specific structural units within range of complete exploration at an early stage.

* The few examples in this and corresponding subheadings are listed merely for illustration.

Copper sulphide ores of Northern Rhodesian type (in part).
Roan Antelope Mine, N. Rhodesia.

Veins, lodes or pipes, or ore shoots in them, bottomed within reach of relatively easy exploration.

Primary mineralization in downward converging bodies in many porphyry copper deposits.
Ely, Nev.

Downward converging ore pipes.
Platinum ore pipes of the Bushveldt, Transvaal.
Certain massive sulphide or breccia copper ore pipes.

Termination of veins or ore shoots at definite limits established by a flat petrological or structural locus of some sort.
Cobalt, Ont.

Restriction of ore to a shallow hypogene zone in certain epithermal deposits.
Individual ore shoots at Guanajuato, Mex.

Limitations imposed on persistent ore bodies by property boundaries.

Veins or lodes dipping across boundary planes.
Outcrop mines on the Witwatersrand, Transvaal.

Ore shoots or lodes plunging across boundaries.
Ore shoots in the central group of mines at Broken Hill, N.S.W.

Flat ore bodies or ore shoots extending beyond boundary planes.
Specific mines in Tri-State district (Mo., Okla., Kan.).

II. PARTIMENSURATE DEPOSITS.

Sedimentary ore deposits in inclined folded or faulted beds.

Bedded iron ores extending beyond practical range of complete development.
Birmingham iron ores, Ala.
Iron formations of the Old Ranges (Mich., Wis. and Minn.).

Residual enrichments along deep loci.

Iron ore shoots along deep troughs.
Ore bodies in Old Ranges (Mich., Wis., and Minn.).

Widespread sulphide ores (or their oxidized equivalents) in flat or gently inclined limestones remote from known intrusives.

Lead-zinc ores of the Mississippi Valley type.
Southeastern Missouri lead district.
Tri-State lead-zinc district.

Concordant veins, lodes, or reefs, in beds or flows, in inclined structures persisting to great depths.

Native copper lodes of Lake Superior type.
Lodes of Keweenaw Point, Mich.

Copper sulphide lodes of N. Rhodesian type (in large part).
Mufulira, N. Rhodesia.

Gold ores of the banket type.
Witwatersrand gold field, Transvaal.

Ores with close magmatic affiliations.

Platinum-bearing layers in ultra-basic rocks.
Merensky horizon, Bushveldt.

Chromite layers.
Bushveldt and Rhodesian chromite deposits.

Magnetite layers or lenses in igneous rocks, generally syenitic.
Mineville, N. Y.
Kiruna, Sweden.

Copper and copper-nickel sulphide ore bodies, as layers, lenses or pipes of major size, massive or disseminated, in relatively fresh igneous rocks.
Sudbury, Ont.

Massive sulphide replacement lodes, lenses, mantos and pipes of major size in highly altered rocks, persistent as individual bodies or repeated along well defined loci.

Pyrrhotite gold ores.
Morro Velho, Brazil.

Pyrrhotite copper gold ores.
Noranda, Que.

Pyritic copper ores.
Rio Tinto, Spain.
United Verde, Ariz.

"Crater margin" ore bodies.
Cerro de Pasco, Peru.

Hypothermal lead-zinc-silver lodes.
Broken Hill, N.S.W.

Pyrometasomatic deposits of large size.
Fierro, N. M.
Highland Boy Mine, Bingham, Utah.

Copper and copper silver limestone replacements of major size.
Morococha (in part), Peru.
Bisbee (in part), Ariz.

Lead-zinc-silver limestone replacement ore bodies of major size.
Leadville, Colo. (in part).
Santa Eulalia, Chihuahua (in part).

Lodes of discordant and concordant stringers, constituting ore bodies concordant with inclined or folded layered structures persisting to great depths.

Continuous gold-bearing lodes of quartz stringers and mineralized rock along well defined loci.
Homestake ore bodies, S. Dak.

Repetition of separate gold-bearing lodes along well defined loci.
Dome Mine, Ont.

Continuous zones of gold-bearing stringers in barren rock.
Alaska-Juneau Mine.

Steep continuous veins or lodes, discordant wholly or in part to layered structures, if any.

Gold quartz veins of relatively deep origin.
Veins of Porcupine, Ont.
Mother Lode, Cal.

Siliceous gold-bearing replacements along well-defined shears of relatively deep origin.
Kalgoorlie, W. A.
Kirkland Lake, Ont.

Base-metal veins of moderately deep to shallow origin on strong persistent fractures.
Multimetalled veins of Butte, Mont.
Copper-silver veins of Magma Mine, Ariz.
Copper-silver-lead-zinc veins of Casapalca, Peru.
Silver-lead and silver-copper veins of the Coeur d'Alene district.

Gold-silver veins of moderate to shallow depth of origin, on strong and persistent fractures.
San Dimas district, Durango, Mex.
Pachuca, Mex.

III. EXTRAMENSURATE DEPOSITS.

Mechanical concentrates concealed by later formations.

Ancient gold placers.
Tertiary channels of the Sierra Nevada, Cal.
Deep-leads of Victoria, Aust.

Pyrometasomatic deposits.

Copper sulphide ore bodies, irregularly distributed in skarn zone.
Seven Devils, Idaho.

Limestone replacement ores.

Massive sulphide copper mantos, layers, and pipes.
Morococha, Peru (in part).
Bisbee, Ariz. (in part).

Massive sulphide, lead, zinc, silver mantos and pipes.
Santa Eulalia, Chihuahua (in part).
Tintic, Utah.

Siliceous gold ores.
Black Hills, S. Dak., ores in Cambrian dolomite.

Repetition of relatively short veins or other ore bodies in a broad locus.

Successive flat veins reoccurring in depth in intrusive bodies of restricted size.
Morning Star Mine, Woods Point, Victoria.

Small veins or irregular masses of ore at intervals along or parallel to axes of folds.
Bendigo, Victoria.

Small ore shoots, irregularly distributed in extensive veins.

Rich gold ore shoots in quartz veins.
Alleghany district, Cal.

Flat-pitching discontinuous ore shoots repeated in depth.
Norseman district, W. A.

Plenemensurate Deposits.

After the initial risks of the prospecting or exploration stage have been successfully passed in mining enterprises based on

deposits listed in this group, uncertainties with regard to ore supply should be largely eliminated. In all of them, the entire extent of the ore-body is within range of exploration generally from the surface, or under some circumstances from mine workings at a lower horizon. In each, the continuity of ore is such that reliable projections can be made between widely spaced intersections. Except for placers that are elongated along river channels, the principal deposits of this group are extensive laterally. Relatively large areas are needed to control adequate tonnage of ore, but once such properties are acquired, the valuable deposit can be traced to its limits or to property lines at an expense that is usually small in proportion to the scale of the proposed or actual investment. The hope of spectacular improvements in deposits in this class is traded for the comforts of security when the exploration stage ends.

Iron Ore Beds and Blankets.—The iron ores that occur in extensive flat sheets, either as beds in sedimentary rocks or as residual surface blankets, offer excellent examples of deposits in which uncertainties with regard to ore supply practically vanish. In the sedimentary ores, the basin of deposition in the major fields—such as Luxembourg and Lorraine—occupies several thousand square miles; the mineralogy and grade of the deposits are remarkably uniform; and the persistence of ore within most of the concessions or other units of ownership can be tested in advance as fully as desired.

In the case of the laterites, exploration is even simpler, for the ore is actually at the surface. Three conditions determine its distribution—an initially iron-rich rock, a physiographic stage of mild relief, and a moist tropical climate. These are rather broad loci, and their intersections, such as occur in Mayari and Moa in Cuba, are consequently likely to be extensive.

Mesabi Range.—The major iron field of the world, the Mesabi Range, possesses characteristics of both the sedimentary type and residual enrichments. Gently dipping beds of iron-formation create a first locus of ore extending as a wide band with northeasterly trend across the region. Conversion of the iron-bearing rock to ore by leaching of silica—a process of residual enrichment

no matter what the active solutions may have been—is restricted, however, to those places where structural conditions favored such action. Two additional structural loci are thereby created, (1) by the confinement of such leaching to ground in which pervasive cracking, probably related in distribution to broad warping cross folds, has increased the relative permeability in the rock, and (2) by the failure of effective leaching to persist very far beneath the feather-edge of the overlying Virginia slate. The latter establishes a southeastern limit to the range; the other subdivides the long broad belt by transverse boundaries. The favorable portions of the iron formation, thus delimited, are almost entirely within range of easy drilling from the surface, and, even though individual ore-bodies are of immense size, exploration has now reached a stage where not only specific properties but the field as a whole, extensive as it is, can be regarded as plenemensurate as far as high grade ore is concerned.

Possibly some slight basis for recognition of a small residual of speculative value in this region is afforded by the hypotheses recently advanced by Gruner[6] whereby enrichment of the iron formation is attributed to leaching of silica by hot rising solutions, instead of by cold meteoric waters as most students of the problem have believed since Van Hise and Leith elaborated the concept.[7] The odds against the soundness of a new idea such as this are high, and very properly so, for it challenges a theory that has been tested by drilling and mine exploration for nearly four decades; but bold speculations, which indicate possibilities for ore that would be ruled out under an orthodox view, deserve especially careful testing if they appear to have any merit at all.

Supergene Ores.—Supergene ores formed from earlier sulphide deposits introduce a few other considerations. Certain bodies of oxidized ore that constitute mining and metallurgical units, as in the case of the silver "pacos" ores of Cerro de Pasco or the far

[6] Gruner, J. W.: Hydrothermal oxidation and leaching experiments; their bearing on the origin of Lake Superior hematite-limonite ores. ECON. GEOL., 25: 697–719; 837–867, 1930.

[7] Van Hise, C. R., and Leith, C. K.: The geology of the Lake Superior region. U. S. Geol. Surv., Mon. 52, 1911.

more valuable body of copper sulphate ore at Chuquicamata, may properly be regarded as plenemensurate, even though they are merely the superficial altered portions of deeper sulphide bodies, which are still to be fully explored. The exploitation of the carbonate ores of Ajo deserves mention here as an excellent example of a successfully completed mining and metallurgical venture for which the ore supply was completely and accurately established at an early stage.

"Porphyry copper" sulphide ores fall into two distinct groups from a valuation standpoint, viz. (1) those in which commercial ore is restricted to the layer in which supergene sulphide enrichment was effective, and (2) those in which the hypogene mineralization is of mineable grade even in the absence of supergene enrichment. In deposits of the first group, a pervasive primary mineralization, spreading throughout immense masses of crackled rock in an intrusive body or its immediate walls, and secondary enrichment, an equally pervasive by-process of weathering, have combined to create ore-bodies that can usually be accurately and completely measured to limits determined by current requirements for profits. In the initial decision to undertake systematic drilling or other expensive exploration, much necessarily depends on interpretation of geologic and mineralogic signs of the most subtle sort, but the nature of these deposits is such that direct data concerning tonnage and grade of available ore, sufficiently complete for long range planning, can be secured before the much larger commitments necessary for mining and milling operations need to be made. To be sure, technical improvements that materially lowered costs added vast tonnages to the ore reserves at the Miami Mine. In certain others, the extreme limits of ore are still to be revealed, but, generally speaking, a stage is reached fairly soon after production starts in most of these operations when the present value of further increments to the ore reserves no longer justifies continued expenditures on exploration. Under such circumstances, the deposit may properly be regarded as plenemensurate.

Since the discovery of the Colorada ore pipe in Cananea beneath lean superficial mineralization of the "porphyry copper"

type, some hopes have been aroused that similar ore-bodies might have escaped detection beneath layers of disseminated sulphide ore in other districts. This speculative possibility is not to be brusquely dismissed, for the concept that richer ores might exist in more restricted feeding channelways in depth has much to commend it; but in the active "porphyry copper" properties the value that can be attached to it in the absence of any positive evidence is still nominal in comparison with that derived from the immense tonnages of proved ore. Perhaps, however, in the very distant future, when longer chances are justified and when better geologic guidance is available, bolder exploration may reveal such bonanzas, possibly even beneath intervening layers of unenriched disseminated sulphides.

Steep Veins.—Mines developed on steep veins are rarely to be placed in the plenemensurate class, except where the lower limit of ore can be definitely predicted on structural grounds and confirmed by tests of some sort at an early stage, or where the pitch of an ore shoot carries it across the boundary plane of the property.

At Cobalt, for example, mining operations soon revealed that the narrow rich silver-bearing veins were confined to a vertical range within a flatly dipping locus a few hundred feet thick parallel to the base of the conglomerate. Though the possibilities of the district as a whole were not capable of being completely measured even in its most active years, operations on individual veins within specific property boundaries were promptly seen, in most cases, to be restricted to predictable limits.

Confinement of rich gold and silver ores to a shallow vertical range, as in a number of western districts of the epithermal type, may give rise to comparable situations. These deposits are rarely fully measured to the extent that all their vagaries can be anticipated and included in an estimate of tons and grade at an early stage; but in a sense their measure is taken when the lower limit of ore in a district is recognized, which should be possible long before they have been completely delimited by formal development.

Broken Hill Lode.—A striking illustration of a plenemensurate

ore supply determined by property limits is afforded by the group of mines that includes the central part of the great Broken Hill lode. Starting on the most spectacular outcrop of the district, these great companies (such as the Broken Hill Proprietary, the Sulphide Corporation, and others) were promptly rewarded with huge tonnages, but soon found that their ore-bodies were bottomed at depths of not much more than 1,000 feet; whereas their neighbors to the north and south, whose ground includes the drooping ends of the sausage-shaped zone, have not yet exhausted their possibilities for deeper ore.

Partimensurate Deposits.

Expectation of profits from ore still to be developed is a substantial part of the total value of all mines on deposits of the types listed under this heading. Ores of sedimentary origin and ores formed by residual enrichment are again noted; but in this group they possess structural characteristics that make their complete exploration at an early stage impractical.

Sedimentary Iron Ore Beds.—The inclined beds of iron ores in the Birmingham district, for example, extend downward beyond the range of economical drilling at intervals close enough to block out ore, though it might be argued that even a few very widely spaced intersections are all that is needed to give assurance of persistence in an ore of such uniform character. In the old ranges of Michigan, steep dips in the iron formation carry the major locus of ore to great depths within relatively short horizontal distances. Furthermore, in these deposits the ore is restricted to inclined troughs that constitute secondary relatively restricted loci within the far more extensive iron formation. Ore shoots, aligned along them, pitch with the folds to limits still not reached in many old mines or reoccur in depth with their successive repetition. Under these conditions, complete exploration of all ground with promise of ore is rarely possible until a mine is close to extreme limits in its old age. But, on the other hand, the ore in specific bodies is continuous and regular in quality, the individual ore shoots are large, the character of the mineralization shows little change laterally or in depth as far as metal content is

concerned, and the ore is restricted to well defined petrologic and structural loci which are capable of projection and prediction. Consequently, from the assurance of ore given by this geological evidence, most of the mines on these deposits can claim a substantial increment of value beyond that based on their measurable reserves.

Michigan Copper Lodes.—The native copper lodes of northern Michigan afford good examples of extensive tabular ore-bodies persisting to depths that have made complete exploration still unattainable in certain mines even after three-quarters of a century of operation. The faithfulness with which these great lodes are confined to specific conglomerate beds and to lava flow tops of distinctive sort and the exact way in which they conform to the inclination of the enclosing layered formations make the projection of the favorable horizons throughout a given block of ground largely a matter of straightforward structural geology. Conditions that determine the location and dimensions of individual ore shoots within these definite but extensive loci, however, are less clearly established. Limits of ore may be correlated with changes in thickness of conglomerate or in texture of a flow top, with warping cross folds or other relatively minor structural features, or with progressive decline or increase of specific minerals or elements, and these features to some extent may be reduced to mappable terms that are capable of projection. Fortunately, long experience has demonstrated that changes in quantity and quality of the mineralization are gradual, and with ore shoots possessing strike lengths that exceed 10,000 feet and dimensions parallel to the dip as great as 8,000 feet their effects can be anticipated considerably in advance of operations. Although the greatest mine on the major lode of the region has reached the lower limit of what is today commercial ore, the bottom for the district as a whole is still unknown. That extreme old age has been attained in these operations is, unfortunately, all too apparent, but it is by no means impossible that rejuvenation may occur at some far distant time in the future when scarcity of metals and high prices may justify deeper exploration. The present situation, however, must not be allowed to obscure the past, when the district led the

world in copper production, and when the deepest shafts on the continent were sunk and major expenditures were made with justifiable confidence that the potential ore supply exceeded even the fairly generous limits of formally blocked out reserves.

Witwatersrand Gold Field.—The Witwatersrand gold field exhibits many similarities to the Michigan copper district. The gold-bearing conglomerates or banket layers, however, have even more remarkable persistence than the copper lodes and their projection to remote limits is made with a degree of confidence that is amazing to any one not familiar with these extraordinary deposits. Ore reserves on the Rand, even as measured under the strict standards of sampling and estimation that prevail there, are immense; but, on the other hand, the scale of operations is so large that few mines have more than five or six years supply of ore actually blocked out. In any transaction in which a direct or indirect appraisal of value is made—as in stock market prices, in offers of new shares, or in major capital expenditures of one sort or another—persistence of ore with proper discounts for percentage payability and suspected irregularities is customarily assumed without the least hesitation to distant limits set by boundary planes, structural interruptions, or the lower limit of profitable mining. Indeed, so little distinction seems to be made in valuation between measured tonnages and those indicated by projections that the properties might almost be placed in the plenemensurate class, if it were not recalled that confidence in these extensions of ore, which go far beyond the sampled blocks outlined by drifts and raises, is based almost entirely on geologic evidence.

Whatever the origin of the gold may be, it is a fact established by long experience that the ore follows specific horizons marked by certain thin conglomerate layers and conforms faithfully to their distribution. Relationships between gold and such geologic features as thickness of reef, form and distribution of conglomerate lenses, rock alteration and even certain structural details have been so well established by long experience, reenforced with abundant statistical data, that predictions of ore or of percentage

payability of the reef horizon can be made with good confidence far beyond actual exposures.

The magnitude of the capital expenditures based on geological interpretation of evidence from widely spaced drill holes is breath-taking. In the last half dozen years, development of the deeper parts of the Far East basin between the Sub-Nigel on the south and the Anglo-American properties to the north has been in progress, which will eventually result in continuous underground workings from one side to the other of the broad syncline, a distance of about 18 miles. With the reef horizon at depths between 5,000 and 8,000 feet, drill-holes obviously cannot be put down at sufficiently close intervals to afford enough samples for reliable determination of average grade. But in spite of the meagerness of positive data of the usual sort, shafts that are among the deepest in the world are being sunk by experienced mining groups with confidence that payable ore shoots persist through these favorably situated areas.

Even more striking is the exploration on the opposite side of the field, largely under the direction of New Consolidated Gold Fields, Ltd., where an extension of the reef to the southwest has been traced for thirty-five miles beneath three unconformably overlying formations—the Ventersdorp lavas, the dolomite of the Transvaal System, and in a few places a hundred feet or so of sediments of Karoo System.[8] By brilliant geologic interpretation from magnetometer surveys, old bore hole records, and a few observations of structure on somewhat remote outcrops, the position of the reef horizons was predicted and subsequently confirmed by deep drill holes. With the evidence on the stratigraphy that they provided, the principal gold-bearing beds were correlated in a satisfactory way with the productive reefs to the northeast and east, and continuity of formations was established throughout the new areas. Certain holes cut high grade ore; a number of others revealed reef that was below possible ore grade. Little or no weight could, of course, be attached to average grades cal-

[8] Pelletier, R. A.: Contributions to the geology of the Far West Rand (with special reference to west Witwatersrand areas). Trans. Geol. Soc. of South Africa, XL: 127, 1938.

culated from such widely separated intersections, but it was concluded that the proof of existence of gold and of the characteristic mineralization associated with it at these significant horizons made the prospects for ore a sufficiently good geologic risk to justify underground exploration.

Mine development in these western areas on the Rand is extremely costly. Shafts must penetrate 1,200 to 4,000 feet of dolomite and other rocks that overlie the Witwatersrand formation in which the reefs occur. Much of the dolomite is fractured and water-soaked, which greatly adds to the cost of shaft-sinking, as at the Venterspost Mine where the ground at No. 2 Shaft had to be cemented in advance of excavation until a depth of 600 feet was reached. All of the ore lies below the bottom of the capping of later sediments, and the upward extensions of the reef are limited by the vagaries of the unconformity against the Ventersdorp or dolomite formations. The conditions just cited all serve to emphasize the boldness of these ventures, in which expenditures running into many millions of pounds sterling are being made with only the assurance of ore provided by a few dozen drill holes and geologic interpretations.

The development of these properties by a highly competent mining group and the eagerness with which not only the public but conservative mining houses sought participation in them afford most impressive testimony to the faith that can be placed in what in final analysis is "geological ore." And from results attained thus far in the first of the new mines under active development, the faith appears to have been justified.

Although many of the older mines on the Rand have been in a plenemensurate stage for some years, the large majority of the properties are clearly partimensurate. Indeed, in the newer developments, the value attached to ore beyond the limits of ordinary projections from workings or drill-holes is so large a part of the total value of the property that an argument could be made for assigning them even to the extramensurate group. These ventures, however, are still essentially in the exploration stage, and in the usual program of mine operation on the Rand they will

undoubtedly become typical partimensurate mines by the time actual production starts.

In thinking about the Rand, the extraordinary persistence of the ore in specific thin beds of conglomerate, the uniformity of average grade during many years of operation, and the immense tonnages developed and milled are apt to over-emphasize the features that make mining relatively safe and which remove uncertainties with regard to ore. Many serious difficulties do exist, however, such as interruption of payability with changes in the sedimentary character of the reef; folds, faults, and dikes that dislocate the beds; localization of gold in ore shoots (or termination of gold bearing reef along structural lines), and extension of the reefs beneath unconformable cover. The deceivingly easy way in which brilliant results are attained tends to obscure the high degree of professional skill that has been required to achieve them; and also the degree to which decisions of major magnitude depend on appraisals of value that are based essentially on geologic evidence.

Magmatic Deposits.—If we continue to follow the order of assurance of ore supply in reviewing a few types of deposits, certain of the magmatic deposits clearly deserve mention at this point in the discussion. To avoid controversy, only those in which the metallic minerals are generally regarded as crystallizations from a melt—(*i.e.* the strictly orthotectic deposits) will be considered; with sulphide ores of possibly similar origin reserved for later consideration.

The platinum ores of the Bushveldt in the Transvaal, which are as surely of magmatic origin as anything could be, occur in two contrasted structural types, one of which is as persistent as any known ore deposit, whereas the other is made up of small erratic bodies of uncertain and generally limited extent.[9] The extensive layer of platinum-bearing diallage norite, known as the Merensky horizon, which can be traced for scores of miles along the outcrop, is the best example of the first type. It is a gently dipping sheet about thirty feet thick in the remarkably differentiated lower

[9] Wagner, P. A.: The Platinum Deposits and Mines of South Africa. Oliver and Boyd, Edinburgh, 1929.

zone of the norite lopolith. Though only thin and very local ore shoots within it are of a grade that could be mined profitably under present conditions, the tonnage of low grade material that might be developed in the flat layers would undoubtedly be enormous, if some nation should decide to pay double the ordinary price for all the platinum that was available and to store it like gold and silver for some mysterious purpose. The richer ores, on the other hand, are in small pipe-like bodies of very different sort which crosscut the pseudostratification of this extraordinary complex of igneous rock. Although profitable mines have been developed on several of them, the ore shoots have persisted to depths of only 600–1,000 feet and none has contained a large tonnage. These ores of unquestioned magmatic origin, therefore, afford examples, on one hand, of remarkably extensive deposits—likely to remain in the partimensurate class for ages and locally reduced to plenemensurate terms only by property boundaries—and on the other of small erratic deposits which are quickly transformed by exploration from the extramensurate group to disappointingly limited, fully measured deposits.

These contrasts are worth keeping in mind in studying other deposits of this genetic type. They again appear in chromite ores, and possibly might be found in magnetite ores, though on account of the lack of commercial interest in small bodies of iron ore only sheets and lenses of major dimensions have received much attention. The greatest of these, the immense dike-like mass of ore at Kiruna in Lapland, is still in the partimensurate class in spite of the rate at which it is being drawn upon to meet the insistent demands of the times.

The massive sulphide deposits that come closest to being magmatic in origin likewise exhibit contrasts in form and persistence that are very nearly as striking. In this group—characterized by relatively fresh rock minerals in the gangue, by corrosion of silicates by sulphides, by absence or scarcity of rock alteration and low temperature minerals, and by lack of dependence on through-going fractures or other obvious channelways—are found many disappointing small ore-bodies as well as some that rank among the major deposits of the world. In the copper-nickel

district of Sudbury, where the best examples of ores of this sort are to be found, the majority of the larger ore-bodies are still in the partimensurate class, with limits in depth still to be determined. Distribution of ore is controlled by specific contacts and rock types to a degree not as yet matched elsewhere in ores of this sort.

The mere fact that a sulphide body possesses the characteristics of this genetic type at the magmatic end of the sequence, however, is in itself no assurance for especially good persistence. Indeed, less confidence is warranted in assumptions of tonnage beyond the limits of known reserves in most deposits of this sort than in hypothermal or even mesothermal massive sulphide bodies that are clearly replacements along some well defined and persistent structural feature. Such ores may occur as large individual masses of continuous sulphide—such as the United Verde ore-body at Jerome—or as a succession of ore-bodies repeated at intervals along a favorable locus. The pitch of axes of ore shoots, the alignment with structures of adjacent rocks, the convergence or divergence of walls, and changes in form and mineralogy are among the characteristics that provide basis for conclusions with regard to persistence of individual masses of ore. Recurrence of favorable conditions along a broad locus may also indicate prospects for tonnage in a given mine far in excess of that in reasonable extensions of any single known body. In the early years at Noranda, for example, both types of prospects for ore existed—*i.e.*, continuation of known ore-bodies and repetition of lenses within the mass of mineralized rock. Recognition of these possibilities for increments to the rather meager tonnage of measured ore led to the bold expenditures that brought this enterprise so promptly to the producing stage; and incidentally gave enhanced value to the immense ore-bodies that were subsequently encountered.

Steep Veins and Lodes.—Problems of rather different sort are encountered when one turns to veins and lodes, in which distribution of ore is determined primarily by the fractures or systems of fractures in or along which the deposits were formed. With relatively steep dips, maintenance of ore reserves requires develop-

ment of successively deeper levels, each of which represents a substantial financial outlay on which no return is realized until the metal or intermediate product that is made available is sold. Consequently, such exploration is rarely carried farther ahead than is necessary to provide for stoping at the desired rate without risk of interruption or to afford a minimum guarantee of value for further capital expenditures. More than this partakes of the nature of insurance, comforting to owners and to those dependent on the enterprise, and desirable within reasonable limits, but not worth too large a price. It is not surprising, therefore, to find that measurable ore reserves in both large and small mines on steep veins and lodes rarely account for more than a fraction of the present values that can reasonably be placed on the properties.

Hypothermal Lodes.—Among the most persistent ore deposits known are quartz-gold lodes of the hypothermal type, in which short veins or lenses with accompanying mineralization are distributed through a mass of ground with sufficient gold to allow it to be mined in bulk. Such deposits are characteristically in metamorphic rocks and were presumably formed at relatively great depth. The lodes, although made up of small and irregular units, most commonly conform to structures in the host and wall rocks with a faithfulness that facilitates projections and gives confidence to predictions for ore beyond the limits of development.

The three largest ore-bodies of this type on the continent are those at the Homestake Mine, at the Dome and other mines at Porcupine, and at the Alaska-Juneau Mine, respectively. Each of these has its own distinctive features, yet in each the ore shoots are essentially broad lodes made up of swarms of more or less systematically arranged quartz seams, lenses, or saddles, conforming to definite boundaries in folded metamorphic rocks.

At the Homestake Mine, individual lodes (or ledges, as they are called locally) not only are confined to one layer of distinctive rock in a series of ancient folded sediments, but they are aligned along structural axes which, in spite of complications of several orders, can be traced along the plunge for distances of many thousands of feet. Although certain ore shoots have terminated in depth and others have appeared, the main ore zone as a whole

(except for interruption by Tertiary intrusives) has contained continuous ore from the surface to the present bottom levels, through which range only nominal changes can be detected in the mineralogy. The large size of the lodes at the Homestake has made it possible to maintain substantial ore reserves without an excessive amount of development in depth in advance of mining; yet at no time in the past have they given a full measure of the value of the mine. Prospects for additional ore, strengthened by the regularity of mineralization and the clearly revealed structural controls, have always been an element of value, although their present worth at any given period has necessarily been substantially reduced by deferment of whatever profits might have been anticipated from them until the end of the life of the known reserves.

At Porcupine, individual ore-bodies rarely are aligned along the axes of folds as they are at the Homestake Mine, but the distribution of veins and lodes through the district reveals a control by the folded lavas and sediments that is just as striking. There, as in the pre-Cambrian rocks of the Black Hills, the gold-bearing solutions introduced their metals along complex systems of fractures distributed in patterns determined by the structure of the previously folded rocks on which they were imposed. Although the dimensions of most of the ore-bodies at Porcupine are essentially those of veins, many of them are made up of a succession of oblique short stringers of quartz and in some parts of the district, particularly at the Dome Mine, these assemblages constitute thick stubby ore shoots that are better described as lodes.

Instead of the closely grouped set of pod-shaped lodes with long axes parallel to the structure, as at Homestake, many of the largest ore-bodies at the Dome Mine have their major dimension oblique or even opposed to the plunge of the folds. As individual bodies, they have a relatively restricted persistence compared with the zone as a whole, but their repetition parallel to an intricately folded minor trough of sediments has given the mine throughout most of its life an assurance of additional ore hardly inferior to that expected in a continuous ore-body of the same type and magnitude.

The Alaska-Juneau deposit, although a product of a much later metallogenetic epoch, differs from the two just mentioned chiefly in the wider spacing of its gold-bearing quartz stringers and in the absence of gold in the black slates and metgabbro between them. The zone, as is well known, is wide and extensive, and the remarkably low grade ore is successfully handled by mining it in a wholesale way and by milling it selectively. The slates, in which the broad lode principally lies, are drag folded as though they had been shoved up the more massive footwall of the greenstones that lie to the west. Older intrusives in the slates—possibly originally more or less sill-like—were involved in the deformation and now occur in elongated bodies with their longer axes parallel to the trend of the minor folds. The swarms of white quartz veins and stringers that make up the lodes likewise conform in a broad way to this general pattern, which reveals structural relationships that are full of meaning to those seeking guidance in development of ore.

No guarantee of persistence is obtained, however, simply because a gold-quartz vein is recognized to be of the hypothermal type. Indeed, as many failures are undoubtedly recorded in prospects on veins of this sort in the Canadian shield as on veins of the notoriously shallow, epithermal type in the west—and far fewer bonanzas although they are not entirely lacking. The outstanding examples of persistence have been vein zones, rather than individual veins. The production of the Hollinger and McIntyre Mines at Porcupine, for example, comes from a succession of strong veins—many of them exceedingly valuable but still merely minor units in the much more impressive total—within a broad mineralized locus that conforms to the prevailing plunge of folded volcanics and intrusives. The downward limits of the zone as a whole are still to be reached, although many specific veins within it have been exhausted. Again, the relationship of veins to folded structures provided the key to distribution of the ore—and likewise provides the confidence for continued success in underground exploration that has for many years given these great mines a value well in excess of that arising from their actually known reserves.

Mesothermal Veins.—The mesothermal group of veins on the whole have an equally good record of persistence. The more regular veins of the Mother Lode in California have been followed deeper than any other deposits on the continent. The ore-bodies on the long breaks at Kirkland Lake, which show affiliation to the mesothermal rather than to the hypothermal ores, are still productive in most parts of the district on the deeper levels, and no clear limits to their persistence can yet be set on geologic or mineralogic grounds.

The multi-metalled veins of Butte, although changing in mineralogy and in structural detail as they are followed deeper and deeper, are still revealing new riches; and again the value of the mines far exceeds the tonnage of their ore reserves. Here, even with the experience of fifty years of production and with a wealth of geologic records of structure and mineralization available for study, I doubt if the local geologists would be willing to predict the total output of copper, silver, lead, zinc and gold with which the district will eventually be credited. Probably, if such predictions were made, they would be over conservative, for geologists and engineers more than others tend to discount the evidence they are best qualified to judge.

Time does not permit a review of the characteristic expectancies of the many types of partimensurate veins, except to say a word of warning about under-rating the lives of districts in which the ore-bodies are classed as epithermal—or shallow-seated and possibly low temperature. The deposits in the district in which mining has continued for the longest time on this continent—viz. Pachuca, where the Spaniards found ore in 1522—are of the epithermal type. Although the depth attained by these deposits is moderate, it is substantial enough to have given the large block of intricately cracked ground possibilities for ore that even yet are not completely and exhaustively tested. In the San Dimas district, in Durango, ores of similar type have been mined through a vertical range of nearly 3,000 feet and in Casapalca, Peru, a strong vein of the leptothermal group has been producing silver, copper, lead and zinc from its outcrop close to the top of a 17,000 foot peak to a level almost 4,000 feet below.

In deposits of this type, however, and more particularly in the truly epithermal deposits, termination of ore with changes in wall rock, with differences in the fracture pattern, by loss of a valuable constituent in passing into a deeper hypogene zone, and with other subtle influences, unfortunately, are all too common. Failure of ore simply by disappearance of the valuable metallic minerals from a vein at some characteristic depth is another danger not to be ignored in ores of this type. Indeed, deep exploration in certain old districts of epithermal veins, such as Guanajuato, for example, where mine after mine has ended at relatively shallow depths, could be regarded as nothing but stubborn blindness to unpleasant facts. What speculative chances such districts still possess are not for ore in depth, but in exploration of shallow ground where less obviously exposed ore may still be concealed.

In spite of such limitations, however, chances for bonanza ore are so large an element of value in deposits of this sort that few, if any, of the larger mines in these districts, some of which are older than any on the continent, could be regarded as fully developed until their very last years. In the modern era, when holdings of individual companies were more extensive and exploration less haphazard, many of them have possessed ore reserves not inferior to those in mines developed on deposits commonly regarded as more persistent; but even in these highly successful operations, there have usually been periods in which their chief value was determined not by ore exposed for routine measurement and sampling but by prospects for ore that seemed promising to those skilled in reading the signs which the epithermal deposits display to the literate. At such times, they could properly be regarded as extramensurate and cited among the examples of this group that are briefly reviewed in the following paragraphs.

Extramensurate Deposits.

Although a comfortable margin of assured ore exists in most smoothly running mines, there are a few in which the nature of the ore-body practically enforces almost exclusive dependence on

geological evidence. Representatives of a number of genetic types may be assigned to this group, but in each case they will be found to be deposits not easily delimited by economically practical means. Ore shoots too erratically distributed throughout a locus that is too large to be systematically explored, those in extremely heavy or wet ground too costly to keep open except immediately in advance of mining, isolated repetitions of ore or recurrent bonanzas that create sudden but short-lived prosperity after intervals of profitless operation may all serve as sources of ore for successful and even long-lived mines; but in them the danger of failure from lack of ore usually justifies so high a risk rate in the valuation formula that their present value is substantially reduced, unless the geologic evidence is unusually persuasive.

Shortage of ore reserves can, of course, arise in mines of many sorts where stoping is allowed to press too closely on exploratory development, but in the deposits classed as extramensurate, this condition is the rule rather than the exception.

Placer Deposits.—Even placer deposits are represented in this group, for profits from operations on buried channels, such as the drift mines of California or the "deep leads" of Victoria are notoriously hard to appraise in advance. The channels can be located by drilling and some signs of gold can be obtained, although generally better evidence of the gold content can be inferred from results obtained in adjacent workings. In most of those now remaining for exploitation, however, the overburden is so thick that drill holes cannot be spaced closely enough to establish the all-important question of grade, and data from old operations are apt to be sketchy. The certainty that vast quantities of gold remain in these ancient channels justifies the attention that they now and then receive, but their attractiveness as mining risks is lessened by the heavy outlay that must be made prior to positive assurance of grade rich enough to meet the necessarily large operating costs; and even after mining starts little is actually known with regard to the material that will be worked more than a few months in advance. In these deposits, even geology itself affords only nominal help; but by study of the ancient drainage system in relation to bed rock conditions, to veins

that are crossed, and to distribution of gold in the known parts of the channels, helpful predictions are possible in some cases. Lindgren's notable volume on Tertiary Gold Gravels of the Sierra Nevada,[10] for example, undoubtedly has been of immense assistance to those who have been inclined to venture in drift mines.

Bonanza Lodes.—Among the mines that have difficulty in keeping good reserves of ore ahead, those dependent on exceedingly rich ore shoots at more or less irregular intervals in extensive low grade or barren veins afford good examples of extramensurate deposits. In the Allegheny District in California, by far the major part of the production comes from small but fabulously rich ore shoots in much more extensive, strong, but almost barren, quartz veins. In most of the operations there, it has been either a feast or a famine, yet the principal mine has been able to maintain a fairly steady annual production with bonanza material available frequently enough to offset the lean periods. It is, however, very doubtful indeed, if at any given time the ore that could actually be blocked out in the mine workings amounted to more than a nominal part of the value that could fairly have been placed on it. The geologic relationships worked out in Ferguson and Gannett's excellent paper,[11] together with study of records of production and habits of ore shoots on individual veins, would surely furnish better grounds for a valuation in the Allegheny district than any statement of ore-in-sight that might be prepared.

Contact Metamorphic Deposits.—Of very different sort genetically and structurally, but not unlike in the reliance necessarily placed on geologic evidence, are the ore-bodies in contact metamorphic zones and the ores occurring as replacements in limestones more remote from the intrusives. In the halo of high temperature silicates known as the skarn zone, copper ore-bodies in particular are fairly common. In a few districts, individual

[10] Lindgren, W.: The Tertiary gravels of the Sierra Nevada, U. S. Geol. Surv., Prof. Pap. 73, 1911.

[11] Ferguson, H. G. and Gannett, R. W.: Gold-quartz veins of the Allegheny district, U. S. Geol. Surv., Prof. Pap. 172, 1932.

ore shoots in such environment may be large enough, as in the Highland Boy Mine at Bingham Canyon or in the older mines at Morenci, to make it possible to block out substantial reserves, but in by far the greater number of such deposits, the ore-bodies are relatively small and so distributed in the broad mass of altered rock that the mine is often hard put to it to keep even a safe working supply of ore blocked out ahead. Although deposits of this sort are particularly common in the Cordilleran Region of the two Americas, few really major mines depend on them alone, although they are to be recognized as subordinate sources of ore in a number of large districts where the principal production comes from limestone replacements farther from the igneous source, or from "porphyry copper" ore-bodies. In mines on ore-bodies of the garnet zone, substantial measurable reserves are usually lacking but geological guidance, provided by the contact itself, by the distribution of rocks and structures of the invaded terrain, and by fracture patterns, as well as by zoning of metals and rock alteration expressed on maps in structural terms, may make it possible to develop ore at a rate that creates confidence in the maintenance of the desired output for some years to come.

Even in the larger districts, such as Bisbee and Morococha, where extremely good ore-bodies occur as replacements in mildly altered limestone well outside what could be described as a contact zone, it is very unlikely if at any time the value of the districts has ever been adequately expressed by their known ore reserves. Yet decisions with regard to major undertakings, such as elaborate plants or long drainage tunnels, have been made without hesitation, even though the life necessary to justify these expenditures depended in large measure on "geological ore."

CONCLUSION.

Except in the clearly defined group in which the available ore supply is completely delimited—in which hazards and opportunities that give zest to mining are almost eliminated—prospects for finding ore in addition to clearly revealed and measurable reserves must be recognized as an element to be taken into ac-

count in any fair appraisal of the value of a mine. Although tonnage and grade of ore that is still to be developed cannot be precisely estimated by routine methods, nevertheless a direct or indirect appraisal of them is made whenever a mine is valued at a higher price than can be strictly calculated from formally developed ore. Estimates of this sort are unavoidably made in the majority of mine valuations and involve assumptions with regard to persistence or recurrence of ore that to be trustworthy must conform to geologic probabilities.

Any attempt to predict specific conditions in the solid rock in advance of exploration necessarily involves risks; but they can be kept to tolerable limits if the appraiser possesses a sound scientific philosophy of what ore deposits really are, supplemented by a shrewd appreciation of their individual vagaries in the many different geologic environments in which they are formed.

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SOME GEOLOGICAL FEATURES OF KOLAR, PORCUPINE AND KIRKLAND LAKE.[1]

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ABSTRACT.

This paper is a comparative study of certain geological features of three of the world's important pre-Cambrian gold-quartz producing districts. Special interest is given to the study because of the productivity and depth persistence of the ore deposits. Features dealt with include (*a*) the place relations of the deposits to granitoid batholiths, regional structure and sedimentary belts; these are shown on maps and are discussed; (*b*) the interrelation of intrusion, deformations and ore deposition in time and place, summarized briefly; (*c*) genetic classification and origin of the lodes; (*d*) practical considerations based on the summarized data.

To the end of 1937 the Kolar district in Mysore State, south India, and the Porcupine and Kirkland Lake districts in northern Ontario, Canada, have produced collectively about 50 million ounces of gold. Some 385 million dollars in dividends have been paid (Table 1). The major ore zones of the three districts have shown depth persistence and promise to continue still deeper. Continued profitable production is assured by substantial ore reserves.

The deposits of the three districts are outstanding representatives of gold-quartz lodes of pre-Cambrian age in early pre-Cambrian rocks of the pre-Cambrian shields. Their geological environments are analogous but with instructive dissimilarities as well. Incentive for a comparative study of their geological features arises particularly from their economic importance and the scientific and economic lessons afforded by their similarities and differences.

The present article deals with some features only of a broad and challenging field for investigation. It is essentially a corre-

[1] Presented before the Society of Economic Geologists, New York Meeting, Feb. 14, 1939.

TABLE 1.

PRODUCTION AND DIVIDEND RECORD.

From the commencement of modern production in the Kolar Field and all production in the Porcupine and Kirkland Lake Fields.

District	Period	Tons Crushed or Milled	Total Gold Recovery Fine Ozs.	Dividends Paid
KOLAR*				
4 Major Producers constituting about 95% of the production of the Field	1882–1936	26,062,820	17,515,467	£ 24,488,705
	–1937	766,999†	330,838	519,864
	1882–1937	26,829,819	17,846,305	£ 25,008,569
Other Producers	1882–1936		1,014,800§	516,981
GRAND TOTAL	1882–1937	26,829,819	18,861,105	£ 25,525,550
PORCUPINE‡	1910–1936	55,544,125	18,813,024	$132,015,935‖
	–1937	4,303,137	1,120,478	12,169,765
GRAND TOTAL	1910–1937	59,847,262	19,933,502	$144,185,700
KIRKLAND LAKE‡	1913–1936	17,040,499¶	9,958,326	$100,756,479‖
	–1937	2,380,452**	999,493	20,259,964
GRAND TOTAL	1913–1937	19,420,951	10,957,819	$121,016,443

	KOLAR (4 Major Producers 95% of Production)	PORCUPINE (All Producers)	KIRKLAND LAKE (All Producers)
Ozs. per ton recovered to end of 1937	.665	.333	.564

* Based on "Kolar Gold Field"—Compiled and issued by the Kolar Gold Field Mining Board.

† In addition to this mine rock tonnage, 242,702 tons of tailings were retreated, the recovery from which is included in the total gold recovery of 330,838 ozs.

‡ Based on Bulletin No. 117—Ontario Dept. of Mines, 1938—prepared by A. C. Young.

§ Estimated from a production of £4,617,342.

‖ Also includes bonuses.

¶ Includes 100,690 tons of tailings retreated by Teck Hughes in 1929, 1934, 1935, 1936.

** Includes 41,333 tons of tailings retreated by Teck Hughes in 1937.

lation and interpretation of certain aspects of the geological environment, nature and origin of the deposits of the three districts. In large part it correlates and interprets features described or referred to by other writers and observers. Some sources of information are quoted or acknowledged but it is impracticable to

attempt to acknowledge all. Special acknowledgments are made in a later section.

The reader is referred to the selected list of references at the end of this article, as well as to other references not listed, for fuller information on the geology of the areas than can be given here.

GENERAL GEOLOGY.

The rock formations and sequence of geologic events of the Indian and Canadian pre-Cambrian shields have many similarities, so much so that direct correlations have been made (1, 2).[2] The principal rock divisions of the regions surrounding Kolar and the Porcupine and Kirkland Lake districts are shown in Figs. 1 and

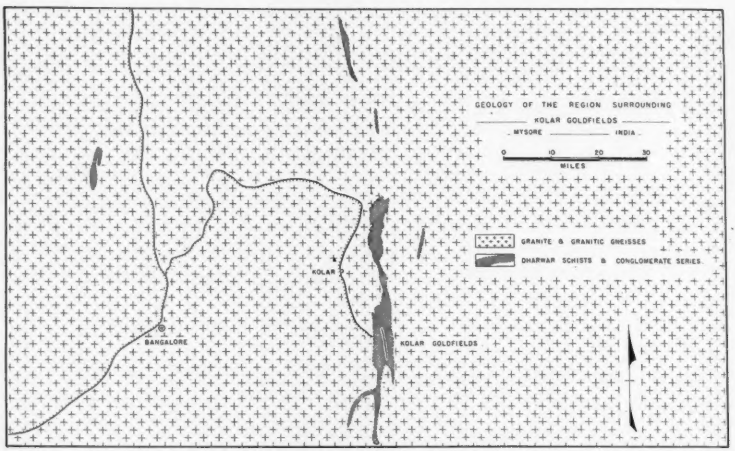


FIG. 1. Based on maps of the Mysore Geological Department. The position of the KOLAR Champion lode is indicated by the line in the Dharwar schist belt, west of the notation "Kolar Goldfields."

2. Most of the rock crust of Fig. 1 is granite and granite gneisses that intrude elongated and irregular remnants of Dharwar schists composed mainly of metamorphosed volcanics with some sedimentary rocks. Various facies of the Dharwar schists are shown

[2] Numbers in parentheses refer to Bibliography at the end.

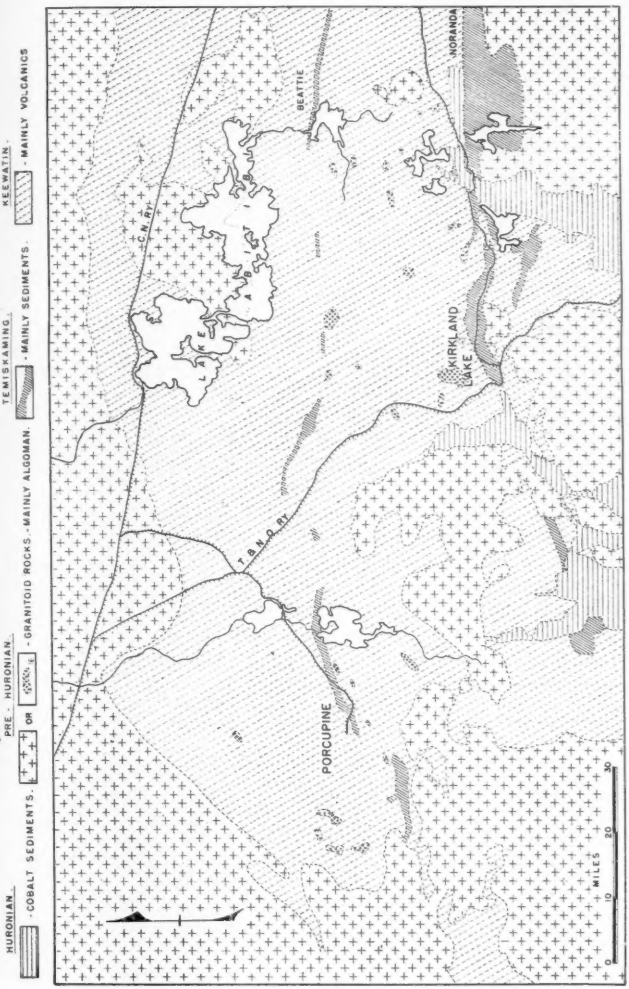


FIG. 2. Based on maps of the Ontario Dept. of Mines with some additions and interpretations by the writer.

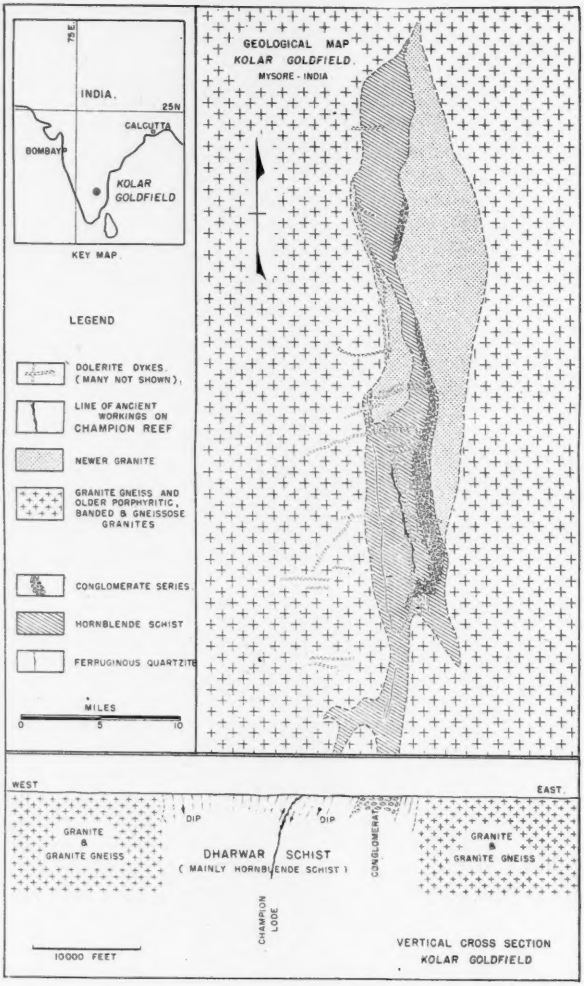


FIG. 3. Plan from maps of the Mysore Geological Department. Vertical cross section interpreted from various information. Drag folds of the Champion lode indicate differential movement (shown by arrows) on the east limb of a syncline (see Fig. 9 for details of drag folds). Structure of the Dharwar schist is shown simplified.

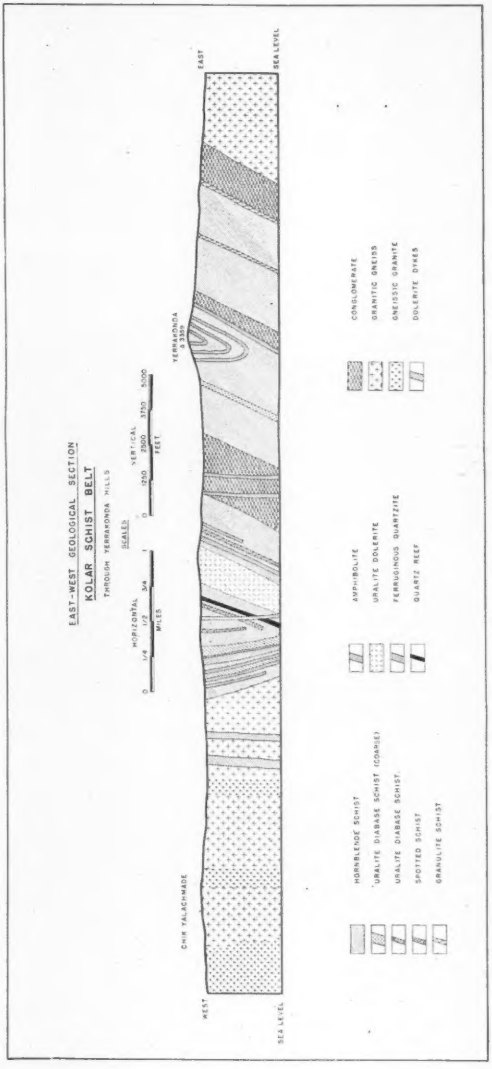


FIG. 4. Courtesy Mysore Geological Department. The section is south of the productive part of the KOLAR Goldfield.

in Fig. 4. The Kolar gold field is in a north-south elongated belt of Dharwar schists, about 50 miles long and ¾ to 4 miles wide. Grouped with the Dharwar schist areas of Fig. 1 and shown separately in Fig. 3, is a belt of conglomerate. This has been interpreted by some geologists as an auto-clastic and by others as a deformed sediment. The field relations seem to favor the latter interpretation (Figs. 3, 4). The conglomerates are shown interbedded and folded with the Dharwar schists in Fig. 4. Fig. 10 is a photograph of the conglomerate.

The granitoid batholiths and stocks of Fig. 2 intrude the Keewatin and Timiskaming. The Cobalt sediments are deposited on the eroded surface of all the other formations shown on this map. Like the Dharwar schists, the Keewatin is composed mainly of metamorphosed volcanics with some sedimentary rocks. The Porcupine and Kirkland Lake gold fields are in the same broad and extensive area of Keewatin rocks and in or near relatively narrow belts of Timiskaming sedimentaries.

As Figs. 1 and 2 are areas of equal size—about 90 miles by 150 miles—the maps give a comparison of the relative areas of granitoid and invaded rocks exposed at the surface of the two regions. The topography of both regions has low relief.

AREAL AND SPACE RELATIONS OF DEPOSITS TO GRANITOID BATHOLITHS.

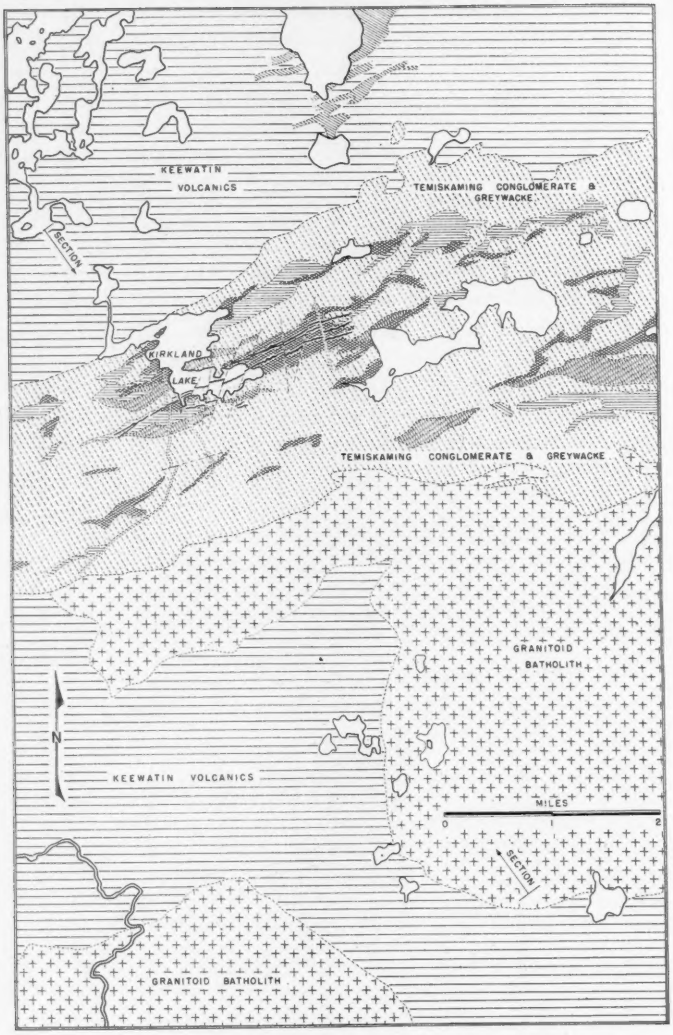
The major ore zones of the three districts share the following relations to granitoid batholiths:

1. They are well outside of, rather than in or against, the batholiths.
2. Considered regionally they are well below the highest parts of batholiths, that is they all occupy depressions in batholiths.
3. Though the relations to probable major underlying batholithic masses are unknown, it is certain that ore deposition extended upward by distances measurable in miles from any possible underlying major batholithic body.

Variations may be summarized as follows:

1. Kolar and Kirkland Lake major ore zones are relatively close to exposed granitoid batholiths, as compared with Porcupine major ore zones. The variations are measurable in miles. This

FIG. 5. After M. E. Hurst. The principal ore zones of the area strike northeasterly and include (*a*) The Pearl Lake area zone (Hollinger to Coniaurum) (*b*) The Dome zone (*c*) The north contact zone of the Timiskaming east of the Burrows-Benedict Fault (*d*) A zone lying south and southwest of the Dome zone (including Buffalo-Ankerite). Note that all these zones are on the limbs of the major syncline of the area.



GEOLOGY OF REGION SURROUNDING KIRKLAND LAKE.

FIG. 6. Based on maps of the Ontario Dept. of Mines. The major ore veins strike northeasterly through the south part of Kirkland Lake. Numerous syenite (albite) porphyry intrusives not shown.

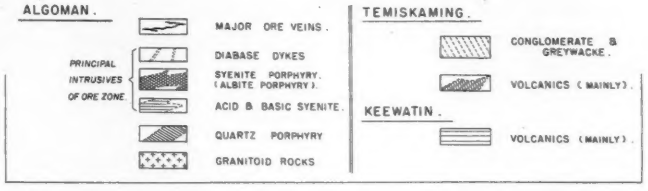
is apparent from the areal geology, in horizontal measurement, and is almost certainly true in three dimensions.

2. The Kolar ore zone lies in a deep trough in granitoid masses. Kirkland Lake ore is relatively close to one side only of a granitoid body. The space relation of Porcupine ore zones to the nearest known granitoid bodies is not indicated clearly though it might be inferred reasonably that the nearest batholithic margin lies to the south.

The evidence for these conclusions is contained mainly in Figs. 1 to 8.

At the surface the Kolar Champion Lode is about 2 miles west and east of batholithic bodies. It is clear, of course, that the tops of the nearest granitoid bodies extended far above the developed lode. Mine development to over 8,000 feet vertically below the surface discloses no underlying granite. Since the ore must have had vertical extension above the present erosion surface, it is clear that ore deposition above any possible underlying granitoid body extended to distances measurable in miles. As the vertical section of Fig. 3 shows, the ore occupies a deep trough in the granitoid bodies.

As Fig. 2 shows, the margins of the nearest large outcropping batholithic bodies to the Porcupine major zones lie to the south about 6–7 miles. A northeast trending chain of small outcropping granitoid stocks passes about 1½ miles south of the south part of the major producing mines of Porcupine. Considered regionally, that is, over distances embraced in Fig. 2 for instance, it is clear that Porcupine ore lies well below the highest parts of batholiths of the region. Mine development to a vertical depth



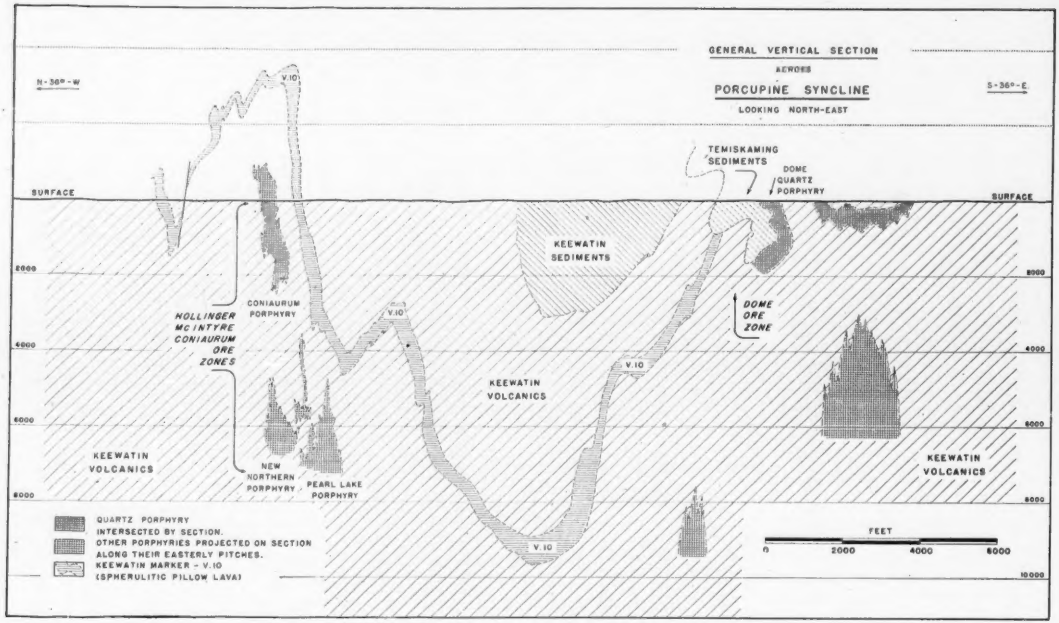


FIG. 7. Based on Ontario Dept. of Mines maps and various other information, especially from D. R. Derry and M. E. Hurst. Note the position of the two principal ore zones on the limbs of the major syncline and the indicated major differential movements shown by drag folds. The major syncline, subsidiary folds, and porphyry bodies all pitch northeasterly.

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FIG. 8

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of about a mile discloses no granite and the outcropping lodes are strong at the surface. Ore deposition extending miles above any possible underlying granitoid body is practically proven. The inference that the nearest batholithic margin may lie to the south is based upon the chain of outcropping granitoid stocks referred to.

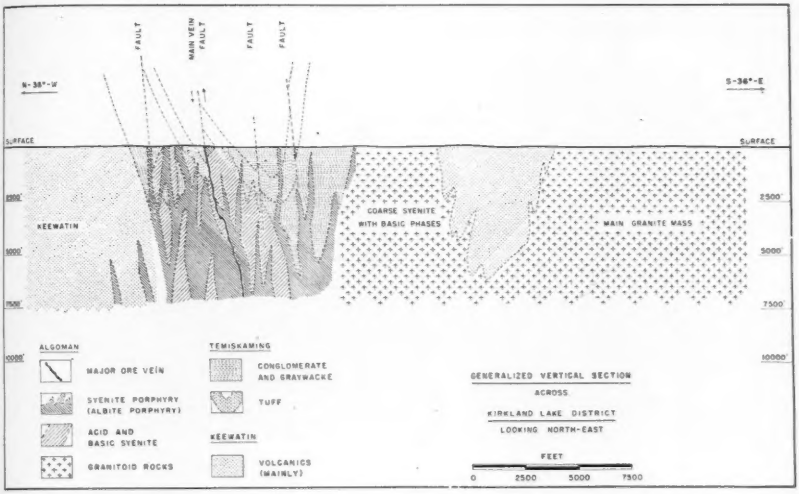

FIG. 8. After Todd (15) with some modifications. Numerous small intrusive bodies not shown.

Figs. 6 and 8 show the known Kirkland Lake relations. The ore zone has been proven to extend downward for over a mile below the present upper surface of the granitoid body to the south. There has been no indication of approach to a possible underlying major granitoid body by mine development to over 6,000 feet vertically below the surface and the relation of faulted segments on the major ore bearing fault proves that no such body is present for several thousand feet deeper at least. The intrusives of the ore zones, shown in Fig. 8, cannot be regarded as granitoid bodies as they are obviously differentiated products of hypabyssal

and M. E. Hurst. Note the position of the two principal ore zones on the limbs of the major syncline and the indicated major differential movements shown by drag folds. The major syncline, subsidiary folds, and porphyry bodies all pitch northeasterly.

characteristics. The present erosion surface exposed strong ore veins. Ore deposition extending upward above any possible underlying major granitoid body for miles is practically certain. As Fig. 8 shows, the main vein is about 7,000 feet from the side of a granitoid body but unlike Kolar (Fig. 3) there is no evidence of a relatively close granitoid wall on the other side of the ore zone.

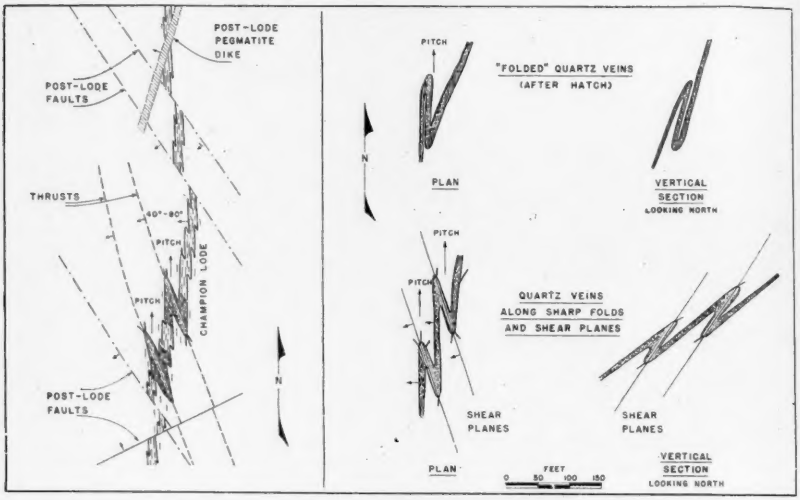

FIG. 9. Left—A part of the KOLAR Champion lode and associated structures and pegmatite. Illustrates time and structural relations. Partly generalized and diagrammatic. Right—Oriented Champion Lode folds and shears.

STRUCTURAL FEATURES.

The ore zones of all three districts are in synclinal zones and the major ore zones are on the limbs of major synclines. Shearing movements caused the lode fissuring of the three districts. Recurrent compressive forces[3] responsible for regional folding

[3] Where this term is used in this article it includes both non-rotational and rotational stresses.

are probable causes of these shearing movements. The notable productivity and persistence of the major ore zones of the three districts reflect the complexity, strength and persistence of the major lode fissures.

According to Hatch (3) a synclinal structure of the Kolar Dharwar schists is indicated by "a converging dip from opposite sides of the belt; the dip on the west side being to the east and on the east and in the central zone, to the west." Quartzite beds

FIG. 10. Pre-Cambrian conglomerate, KOLAR district, Photograph by E. S. Moore.

(ferruginous and jaspery) dip under the hornblende schist near the western margin of the Dharwar schist belt. On the eastern side, quartzite at Yerrakonda dips westward. Fig. 4 shows these relationships. The vertical section of Fig. 3 shows the relation of the Champion lode to the synclinal structure in generalized and simplified form. Actually the structure is much more complex. The Champion Lode of Kolar—the major ore zone of the district—is on the east limb of the major syncline. The orientation of the drag folds, which are a striking feature of this lode, seems to show this clearly (Figs. 3, 9). Such folds have been interpreted by some observers as pre-vein and by others as post-vein (3, 4) but regardless of the time relations with respect to veining

they indicate a position on the east limb of a north plunging syncline.

The positions of the major ore zones of Porcupine and Kirkland Lake with respect to the regional structure are shown in Figs. 5, 6, 7 and 8. It will be noted that the zones are on the limbs of the major synclines.

At Kolar and at Porcupine, foliation, drag folding, shear planes, thrust faults and subsidiary fissures have all had a part in controlling the disposition and configuration of the veins. Such lode structures must have been produced mainly by compressive forces with resultant shear. The major ore zones of Kirkland Lake occupy strong reverse faults obviously developed by compressive forces with resultant shear.

It seems probable that a recurrence, or a continuation, of the compressive forces responsible for regional folding produced the major lode fissures of the three districts. This does not necessarily imply consistent orientation or resolution of compressive forces (non-rotational and rotational stresses) in harmony with a commonly assumed cause of folding by horizontally applied non-rotational stress. Superimposition upon the folded rocks of a chain of compressive deformations, of which lode fissuring was one link, involved complex resolution of forces. However, certain features suggest that the lode fissures originated by repeated pressure responsible for regional folding. The position of the major shear zones on the limbs of the regional synclines is consistent with experimental and field evidence of accentuation of shearing in such locations on a folded structure by continued application of folding pressures. Drag folds at Kolar and at Porcupine are component parts of the regional folding and some lode shears have been developed by strain of such drag folds. The major ore zones of both districts follow shear zones superimposed upon, and broadly elongated with, the deformed rocks. The displacement on the major reverse veined-faults of Kirkland Lake (Fig. 8) is in harmony with differential movement on the limb of a fold during folding. However, these faults cut both the folded structure and rocks that cut the folded structure. Hence it is clear that the faults are subsequent to the folding.

But that they developed by differential movement produced by a continuation of folding pressures is suggested strongly by the direction of displacement and by the position and attitude of the faults with respect to the synclinal structure.

The major lode fissures of the three districts share the common features of complexity, strength and persistence. Complexity of the Kolar Champion Lode fissuring is brought out in Pryor's descriptions (4). The assemblage of fissures making up the lode channels extends for miles with great persistence along a relatively straight course. Depth continuity of the fissuring is already proven to over 8,000 feet vertically below the surface. Powerful faults cut the foliated rocks. The complexities of Porcupine lode fissuring have been pictured and described by a number of writers (7–10). Individual veins are commonly relatively short but the major shear zone of Porcupine (the Pearl Lake area zone) extends with a persistent northeast strike for many miles. Vertical depth continuity of this shear zone has been proven to over a mile. Powerful shear zones and faults cut the rocks of the zone. Kirkland Lake major ore-containing faults are accompanied in places by complex intersecting or parallel subsidiary fissures and by brecciated, crushed or sheared zones (15, 16). The major veined-fault persists continuously for many miles and vertical depth continuity has been proven to about 1¼ miles and is certain to extend many thousands of feet deeper.

Complexity of fissuring in these three fields results in a multitude of ore shoots in imbricating, branching or parallel veins whose disposition has been controlled by the complex fissuring. Width of mineable ore is promoted in many places by complexity of fissuring. The productive lives of the principal mines of these districts have been enhanced vitally by these conditions.

The strength and persistence of the Champion Lode fissuring has resulted in an output of gold from this lode from a strike length of 4½ miles and to a vertical depth below the surface of about 8,000 feet. The powerful Pearl Lake area shear zone contains important orebodies intermittently over a strike length of about 3 miles and to vertical depths of about a mile. Great

strength and persistence of the Kirkland Lake main veined-fault is reflected in important orebodies disposed intermittently over a strike length of about 3 miles and to a proven depth up to about 6,000 feet.

RELATION OF ORE ZONES AND SEDIMENTARIES.

The relation of the ore zones of the three districts to sedimentary rocks has direct connection with their structural locations. As Figs. 2, 5, 6, 7 and 8 show, sedimentary rocks occupy the synclinal basins of Porcupine and Kirkland Lake. A similar relation is suggested, though perhaps not proven, at Kolar (Figs. 3, 4, and 10). The connection between sedimentation and ore deposition with magmatic affiliation has been discerned by a number of geologists. B. S. Butler (17), for instance, summarizes the situation as follows:

> Certain relations between the formation of ore deposits and other geological processes are pretty generally accepted, namely . . . that folding and faulting are greatest in basins of extensive sedimentation and least in areas of erosion or slight sedimentation; that areas of erosion or slight sedimentation and of heavy sedimentation persist over long periods and exert a major control over *structure, igneous activity, and ore deposition* (the italics are my own). . . . In short, ore deposition is but one phase of a series of closely related geological events.

C. W. Knight (20) has referred to the distribution of important ore deposits in, or not far from, synclinal sedimentary belts in the Canadian Shield. This association appears to be the most prevalent and significant feature of ore distribution in that area. Undoubtedly, the interrelation of heavy sedimentation, deformation and magmatic differentiation of which ore deposition is a phase, accounts broadly for the space association of the deposits and erosional residuals of basins of heavy sedimentation.

RELATIONS OF ORE DEPOSITION, HYPABYSSAL INTRUSION AND DEFORMATION.

The broader time relations of ore deposition, hypabyssal intrusion and deformations are analogous in the three districts, with some interesting differences.

In the three districts pre-ore hypabyssal intrusives were emplaced in already folded rocks. This was succeeded by deformation, including the development of fissures that were later occupied by veins. These fissures cut the intrusives, where these are present, as well as the intruded rocks. Then, after ore deposition, followed faulting of localized development and at Kolar *only* an interesting injection of pegmatite bodies cutting the Champion lode.

The three districts show the same phenomena of intrusion of basic dikes later than salic intrusives, but at Kolar the dikes are much more abundant than at Porcupine and Kirkland Lake and they are pre-ore or nearly contemporaneous with ore deposition at Kirkland Lake and post-ore at Kolar and Porcupine.

In all three districts pre-ore salic intrusives have entered, in part, the same general locus as that occupied by the later ore deposits. Nevertheless, there is much variation in the space relations of orebodies and intrusives in each district and among the three districts. In some places the ore veins penetrate or contact the intrusives; in other places there is complete detachment, in part by considerable or great distances. Space association of major ore zones and salic intrusives at Kirkland Lake (Figs. 6, 8) on the whole is more intimate than at Porcupine and Kolar.

Each of the districts shows the influence, but not strict control, of pre-ore rock folded and other structures on the disposition of the salic intrusives.

The control of wall rock structure on the disposition of lode quartz in the three districts is intimate and universal. Though there is chemical modification of veined-fissures, and there may be a questionable mechanical modification of these fissures by quartz depositing agencies, the intimate control by fissures on the disposition of the quartz is shown everywhere on a large and minute scale.

The genetic connection of the lodes of the three districts to spacially associated salic intrusives appears probable but rests more upon reasoning and generalizations than upon evidence amounting to proof. Because the ore-bearing fissures cut the intrusives and may extend downward great distances below the

upper parts of the intrusives, there is no reasonable basis for regarding the lode quartz as a direct magmatic differentiate of the present exposed hypabyssal intrusives. Part of the reasons for crediting genetic connection between lode quartz and intrusives rests upon their penetration of the same general locus of the earth's crust. Part depends upon the mineralogical and chemical character of the intrusives and the ore, that suggest successive derivation from a common magmatic source. The microgranite ("dogger") of Kolar, the successive intrusion of alaskite (quartz albite) porphyry and albitite at Porcupine, and the successive intrusion of basic syenite, acid syenite and syenite (albite) porphyry at Kirkland Lake, all prior to quartz lode deposition, suggest stages of magmatic differentiation from a common source.

The interrelation of intrusion, deformation and ore deposition, in time and place, is well exemplified in all three districts. The sequence and character of events were much the same, with two principal differences, namely, the pre-ore age of basic dikes at Kirkland Lake and the occurrence of post-ore pegmatite dikes in the Kolar ore zone.

GENETIC CLASSIFICATION AND ORIGIN OF LODES.

Collectively, the lodes of the three districts appear to span the hypothermal to mesothermal genetic classification of Lindgren (18). Mineralogical evidence of this is as follows:

(*a*) Pyroxene, amphibole and brown mica were developed in wall rock of the Champion lode from lode-forming agencies (Fig. 11), (4). These minerals are rare or totally absent as wall rock alterations accompanying lode formation at Porcupine and Kirkland Lake.

(*b*) Carbonates, sericite and chlorite were the principal minerals developed by the attack of wall rock by lode-forming emanations at both Porcupine (Fig. 12) and Kirkland Lake (15). These minerals were developed also in wall rocks of the Champion lode (Figs. 11, 13).

(*c*) Tourmaline, scheelite, pyrrhotite and arsenopyrite are in veins of the Champion lode and in veins of Porcupine and are absent, or extremely scant, in Kirkland Lake ore veins.

These significant features show that the Champion lode is hypothermal but with some mesothermal characteristics; that Porcupine lodes are hypothermal-mesothermal (sharing the characteristics of both) and that Kirkland Lake lodes are mesothermal.

Although differences in the chemical character of wall rocks, and in the chemical character of the ore-bearing solutions, may account partly for the differences in lode wall rock alteration at Kolar as compared with Porcupine and Kirkland Lake, proof that this is not so entirely is afforded by the development of carbonates, sericite and chlorite in the wall rocks of all three districts. There appear to be sound reasons to conclude that the *initial* temperature during Champion lode formation was higher than the initial temperatures during the formation of Porcupine and Kirkland Lake lodes.

Two other outstanding mineralogical features distinguishing Kirkland Lake ore lodes from both the Kolar Champion lode and Porcupine lodes, should be mentioned. These are (*a*) the relative prevalence and abundance of tellurides in Kirkland Lake ore veins (Figs. 14, 17), (15) as compared with Porcupine lodes where they may be present but are not so typical, and as compared with the Kolar Champion lode where they are scant or absent (4) and (*b*) the prevailing reddening of wall rock (15) in and along Kirkland Lake lodes (Fig. 14) due apparently to the development of minutely diffused iron oxide by lode forming emanations. Absence of this effect on wall rocks at Kolar and Porcupine suggests differences in the physical environments during ore deposition as compared with those prevailing during the formation of Kirkland Lake lodes.

In addition to the main lode minerals, the major ore zones of each of the three districts contain later, differing, and locally developed mineral aggregates that were either developed during a late stage of the major ore lode deposition or after a break in that deposition. These late depositions suggest changes in the physical environment, including temperature changes and the probability of great time range of mineral deposition.

Thus, Pryor (4) records deposition in the Nundydroog mine of coarse gold with tetrahedrite and some chalcopyrite in a breccia associated with vugs or open spaces in the Champion lode. Langford and Hancox (12) have described local deposition in the Pearl Lake zone of Porcupine of selenite and anhydrite and they conclude that there is "little doubt that anhydrite is a late

FIG. 11. Polished ore specimen from the KOLAR Champion lode. × 2½.

W.—Sericitized hornblende schist wall rock, composed mainly of quartz, hornblende and sericite and containing also minor shreds of brown mica, some fine-grained pyrite and a few small stringers of vein quartz.

A.—Altered wall rock residuals in dark green bands composed mainly of amphibole and sericite and containing also minor amounts of chlorite, sphene, quartz and brown mica.

P.—Altered wall rock residuals in light green bands composed mainly of pyroxene and small quantities of carbonate, quartz, chlorite, sericite and hornblende. A few shreds of hornblende occur in the well-crystallized pyroxene.

Q.—Well fractured coarse-grained vein quartz.

member of the period of mineralization that gave rise to the auriferous veins." They deduce that this end-stage of mineralization must have produced *a temperature below 30–66° C.* At Kirkland Lake, coarse-grained galena, chalcopyrite, pyrrhotite,

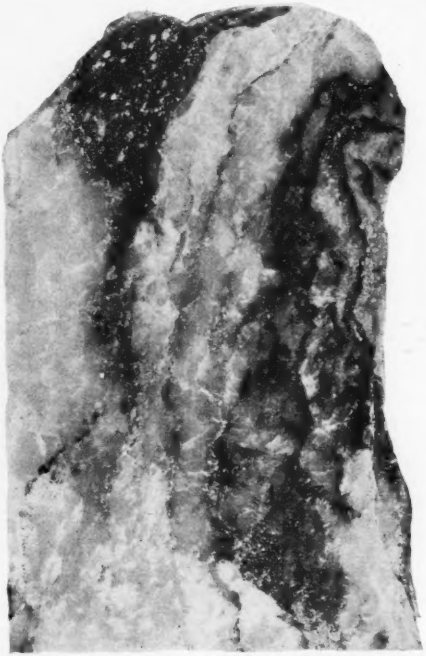

FIG. 12. Polished ore specimen from PORCUPINE (Coniaurum Mine). × 2. Quartz-ankerite vein (gray and white) with altered wall rock residuals containing abundant pyrite. The residuals are composed mainly of carbonates, chlorite and sericite.

specular hematite, calcite and barite are found in post ore-vein faults (15).

The outstanding mineralogical similarity of the lodes of all three districts, is the overwhelming predominance of similar vein-quartz. Although this quartz differs in texture, color and degree

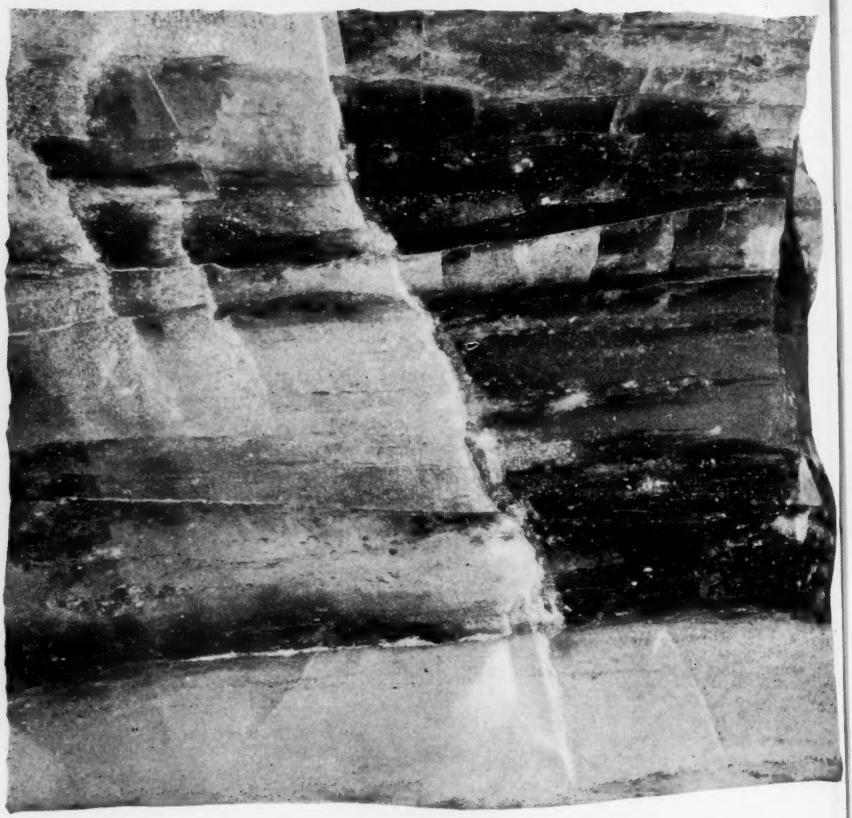

FIG. 13. Polished specimen of rich ore from KOLAR Champion lode (Champion Reef Mine), vertical depth of 8,029 feet below the surface and assaying 100 dwt. gold per ton. × 2½. (Courtesy of John Taylor & Sons.) The quartz (white to almost black) has a cherty (horny) texture. The microscope shows granular quartz aggregates in bands parallel to the banding of the specimen. Some individual grains are elongated in the same direction. Dark streaks are wall rock residuals consisting mainly of sericite with minor brown mica, hornblende, quartz, arsenopyrite, tourmaline, magnetite, sphene, pyrite and free gold in descending order of quantity.

FIG. 14. Polished section of rich ore specimen from KIRKLAND LAKE (Macassa mine). × 2½. Milky to vitreous white and gray fractured vein quartz intercalated with, and including, wall rock residuals of acid syenite, which are invaded by vein quartz and reddened by ore depositing emanations. Abundant fine-grained pyrite occurs mainly in the wall rock and also in the quartz; other metallics are chalcopyrite, tellurides and visible gold.

FIG. 15 (Upper). Deep-level rich ore from KOLAR Champion lode (Champion Reef Mine). Natural size (Courtesy of John Taylor & Sons). Fractured vein quartz contains a few wall rock residuals and abundant coarse gold.

FIG. 16 (Lower). Rich ore from PORCUPINE (4,250 Ft. level, Coniaurum Mine). Natural size. Fractured vein quartz contains wall rock residuals and considerable pyrite, sphalerite and coarse gold.

of fracturing from place to place in each of the three districts and between the three districts, on the whole the same relatively coarse-grained so-called "pegmatitic" quartz is typical of the three districts (Figs. 11–17). The vein quartz of the three districts has been determined by V. B. Meen as low temperature quartz that has not reached a temperature of 573° C. (Ref. 19 for Porcupine and Kirkland Lake; private determination for

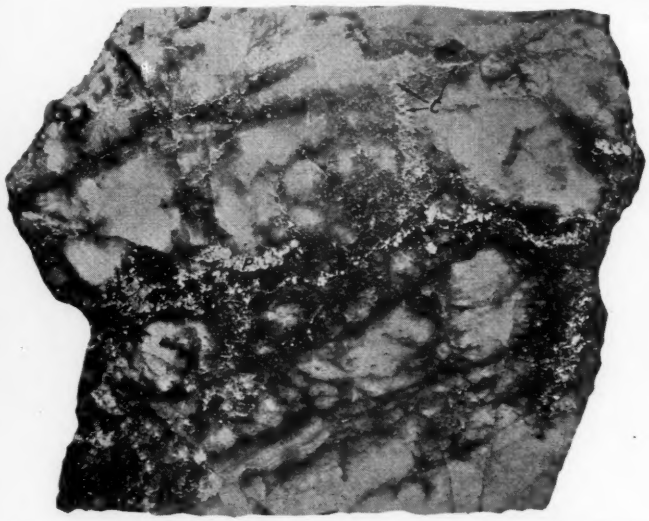

FIG. 17. Polished surface of rich ore specimen from KIRKLAND LAKE (Wright-Hargreaves Mine). After Todd (15). Courtesy Ontario Dept. of Mines. ×2. The highly fractured quartz contains pyrite (P), chalcopyrite and calaverite (C).

Kolar). A further similarity is the prevalent occurrence of vein carbonates, common in the lodes of the three districts (most common in Porcupine lodes). Still another similarity is the same *general order* of ratio of gold to silver in the ores (about 80–90 per cent gold). All of these mineralogical characteristics, common to all three districts, and the additional mineralogical char-

acteristics shared by Kolar and Porcupine on the one hand and by Porcupine and Kirkland Lake on the other, point to the same fundamental origin of the lodes of all three districts. This conclusion is supported by their analogous geological environments as well as by general evidence on this question.

It appears extremely likely that the source of the lodes of all three districts was an underlying magma, *of unknown depth,* and that the deposits were formed from silicic differentiates. This is particularly convincing at Kolar. W. F. Smeeth (5) describes mineral occurrences in the Dharwar schists of Kolar that are characteristic of the vicinity of both aplite intrusives and quartz lodes of the area. These include especially the development of pale green pyroxene at the expense of the hornblende of the invaded rock [4] (see Fig. 11 for an example of its development in the Kolar lode). Other mineral changes attending the aplites and quartz lodes are replacement of wall rock ilmenite by sphene, deposition of calcite and pyrite and the development of bronzy mica. Because of the identical alteration effects along the aplites and quartz lodes, Smeeth reaches the logical conclusion that the aplitic and quartzose depositing agencies were similar. Since it is clear that the aplitic material is a silicic differentiate, related to the granite rocks of the region, it is concluded that the quartz lodes and accompanying mineralization also were produced from silicic differentiates of a granitic magma. Further suggestions of silicic magmatic derivation are given by the tourmaline, scheelite, albite and abundant coarse-grained quartz of the lodes. The proximity of large bodies of solidified granitic magma provides tangible evidence of granitic invasions and silicious differentates from these is a reasonable expectation. Space association of post-lode pegmatites and the Champion lode (Fig. 9) suggest an analogous origin but it should not be concluded hastily

[4] This significant alteration suggests instability of the hornblende due to heat (and possibly other agencies) generated by the invading silicic differentiates. Smeeth states that the secondary pyroxene (augites) are not by any means mere re-crystallizations of the hornblende grains or crystals but are "entirely reconstructed entities." He concludes that the hornblende has been "absorbed or resolved" and has segregated out in the form of augite in larger units.

that they have the same source. Pryor suggests (4) that the pegmatites and lode were emplaced during different periods of granitic invasions.

Quartz-albite, quartz-tourmaline and quartz-scheelite veins at Porcupine and other considerations summarized by A. G. Burrows (7) indicate derivation from silicic magmatic differentiates.

Though such minerals as albite and molybdenite, which occur in small quantities in Kirkland Lake veins, suggest the origin of the veins from silicic magmatic differentiates, on the whole the mineralogy seems to give less convincing evidence of this derivation than at Kolar and Porcupine. The coarse-grained character of the vein quartz and its abundance, analogy with other deposits, the geological setting and history and general geological considerations, are the principal reasons for the prevailing opinion that the deposits originated as silicic magmatic differentiates.

Although the origin of the deposits as silicic magmatic differentiates is reasonable, it does not follow that any exposed portion of a granitic or any other rock body above the known lowest parts of the ore zones, was itself the source of the ore in any of the districts. In fact this seems inconceivable when the space relations are visualized (Figs. 3 to 8). Correlation in time between the granitoid bodies of the regions and ore deposition should be made cautiously. Differences in thermal effects indicated by the mineralogy of the deposits of the three districts may be dependent in part on a time lag between granitic invasion and ore deposition. At Kirkland Lake, an extended sequence of geological events, including intrusion of basic dikes, took place after granitic invasion and before ore deposition and this may have been a factor in determining the mesothermal character of these deposits.

PRACTICAL CONSIDERATIONS.

These should be viewed in the light of the fact that the districts under consideration are centers of extraordinary, rather than ordinary, gold-quartz ore deposition, in the regions in which they occur.

Features of special interest to prospecting and to broad-scale appraisal of the possibilities for regional distribution of ore, include the relations of the ore zones to granitoid batholiths and to regional structure.

Attention is called to the fact that these gold deposits, of extraordinary productivity and depth persistence, are in deep synclines extending far below the tops of the invading granitoid batholiths of the regions and that the upper parts of the deposits, at least, are miles above any possible underlying major granitoid body. Furthermore, the deposits may be many miles (6–7 miles in the case of Porcupine), measured horizontally, from the margins of exposed major granitoid bodies, or they may be relatively close (less than 1½ miles in the case of Kirkland Lake). Probably the most valid generalization that can be made, based upon Kolar, Porcupine and Kirkland Lake conditions is that there is *a wide range* (measurable in many miles) in the distances of the deposits from the margins of batholiths.

The position of the ore zones of the three districts in synclinal basins is of the utmost practical importance. It appears that in these deeply eroded regions, particularly deep major synclinal basins are most likely to be delineated by residuals of belts of heavy sedimentation. Such zones merit special attention as favorable loci for important ore deposition. Localization of the major ore zones on the limbs, rather than in the axial zones, of regional synclines appears to be significant. However, the relation should not be interpreted too rigidly since in tightly folded or narrow synclinal basins there may be narrow space differences between the limbs and axial zone. (Note, for instance, the relations for Kirkland Lake, shown in Fig. 8.) Furthermore, the limb of a syncline is also the limb of an anticline and the principal site of ore deposition may be as close or closer to the axial zone of an eroded anticline as to the axial zone of the syncline.

The presence of powerful and persistent fissured zones is the fundamental physical reason for the productivity and depth persistence of the *major* ore zones of the three districts. The practical value of the recognition of such *major* structures in appraising the potentialities of such deposits is self-evident. The in-

fluence of detailed structures upon the localization of ore shoots in these three districts has not been discussed in detail in this article but the great practical importance of determining and delimiting these structures is apparent. Intimately connected with this are the influences of the ore zone intrusives and other rock bodies upon the localization of ore bodies. Proximity to, or position within, intrusives may be extremely important in localizing ore but such relations are variable and it is of practical importance to realize that ore deposition may have a range extending far beyond the positions of such intrusives.

Useful lessons may be learned from the character and variability of the ore lode mineralogy. These lodes are marked strongly by *hydrothermal* characteristics and, more specifically, by hypothermal and mesothermal characteristics. Mining experience has proven a great depth range, without marked mineralogical changes in kind and quantity of lode minerals or in gold tenor, for the major ore zones of each of the three districts. Based on the experience of the mines under consideration, one is justified in allowing considerable variation in mineralogy without prejudice to the possibility of great depth persistence of gold values, providing the mineralogy is in the hypothermal-mesothermal range. If the experience of other mines, such as Homestake, is added, the mineralogical range consistent with unusual depth persistence is expanded still further.

Finally, the fundamental geological similarities of these great gold-quartz ore deposits inspire confidence in the universality of workable principles that can be used in the search for ore deposits in analogous geological environments. In the midst of variation one discerns causes and effects applicable to many other districts.

ACKNOWLEDGMENTS.

In addition to the bibliography noted below the writer is indebted to many other written sources of information and particularly to the personal cooperation of many mining men and geologists. Messrs. John Taylor & Sons of London, England, consulting engineers of the principal Kolar mines, kindly supplied deep-level ore specimens of the Champion lode and also sent longitudinal

sections of the Ooregum and Champion Reef Mines. James Bichan, who was recently geologist for the Mysore Mine at Kolar, imparted much valuable detailed information on the geology of the Kolar District and particularly on the structure and mineralogy of the Champion lode, including the results of microscopic studies of the rocks and ore. Prof. E. S. Moore of Toronto University, and Prof. F. K. Morris of Mass. Inst. of Technology, both of whom have had field acquaintance with Kolar, contributed information on certain geological aspects of the Kolar region. B. Rama Rao, Director of the Mysore Geological Department kindly sent the vertical section shown as Fig. 4. Dr. V. B. Meen of the University of Toronto made microscopic studies of ore specimens from the Champion lode and also determined the low-temperature character of the quartz of this lode.

Adequate acknowledgment for information on Porcupine and Kirkland Lake geology would include a long list of mining men and geologists in Canada, who have afforded opportunity for the writer's investigations and have contributed verbal information. The indebtedness of any student of the geology of these districts to geologists of the Ontario Dept. of Mines hardly needs emphasis. In bringing Porcupine geological findings up-to-date, the writer had the benefit of personal information and of recent mapping by M. E. Hurst and D. R. Derry who, in recent years, have tied together a number of loose ends in the complicated geology of this district.

25 King St. W.,
Toronto, Ont., Canada,
April 1, 1939.

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OUTCROPS OF ORE SHOOTS.*

HARRISON SCHMITT.

ABSTRACT.

A number of ore shoot "outcrops" and surface expressions or criteria for ore shoots in the Southwest and northern Mexico are described. Safe generalizations on criteria that can be applied from one district to another seem to be limited because the variation in occurrence is large. The obvious method of attack where a district has produced ore is first to study the known ore shoots in their structural, lithologic, and mineralogical environment and then to search for similar frameworks in undeveloped areas. The work should include plane table methods of mapping on large scales, microscopical techniques and studies of the shapes of the ore shoots and the distribution of metals in the ore shoots and metalliferous zones. The quartz spectrograph should give valuable information in tying outcrops to ore shoots, but the high cost of the quantitative type of instruments limits their use in the field.

INTRODUCTION AND ACKNOWLEDGMENTS.

CONSIDERING the usefulness of information relating outcrops to ore in the undeveloped areas, or even in well developed mining districts, the poverty of pertinent descriptive matter even in papers containing detailed descriptions of metalliferous ground, is difficult to explain. Often the chief question that confronts the geologist today when making an appraisal of raw territory is what changes an outcrop will show with depth—whether it will turn to ore or continue as waste, for the extension of ore in depth below an outcrop of ore is a question seldom encountered.

The term *surface expression* is used in this paper as a general term which, besides outcrops of ore, gossan, relict minerals, etc., includes such surface indications of ore below as collapse fractures, faults and breccias, other structural abnormalities, and wall rock alteration, such as marbleization of limestone, hornstonization of shales, bleaching and other color effects.

* Presented to the Society of Economic Geologists, New York Meeting, February 14, 1939.

Most of the published information on outcrops is general in nature. The notable exception is the more or less integrated work of Locke, Morse, Blanchard, Boswell, and others (3, 4, 5, 10, 12).[1] Locke's scholarly book (10), although largely concerned with the cappings of copper ores, not gossans, lists many new facts, indicates the complexity of the general subject, reveals the wide gaps in the pertinent theory and exemplifies a non-empiric attack on the general problem. The literature in general demonstrates the close relationship between outcrop and supergene enrichment problems. The object of this paper is to describe some outcrops studied by the writer and to discuss briefly outcrops in general.

The writer is indebted to F. F. Grout, Augustus Locke, and D. F. Hewitt for criticism of this paper and to the New Jersey Zinc Company and the American Smelting and Refining Company for permission to publish some of the data collected from their properties. G. Austin Schroter did the research on the wall rock alteration summed up on Fig. 5.

OUTCROPS OF CERTAIN ORE SHOOTS IN SOUTHWESTERN UNITED STATES.

Hanover, New Mexico.

The sphalerite ore bodies at Hanover, New Mexico, occur in an environment of contact pyrometasomatism. They are localized by high angle normal faults, the intersection of high angle normal and low angle thrust faults, dike contacts, and fracture zones, and reach their most important development in certain relatively pure limestone beds. The associated minerals are mainly andradite, epidote, salite,[2] magnetite, sphalerite, ilvaite and pyrrhotite. The ore is low in copper, lead, and other metals considered as impurities in zinc metallurgy.

Outcrops of massive sulphide ore containing 15 to 50 per cent zinc and the oxidized equivalent of such ore largely a "limonite" gossan called "bath sponge" by Boswell and Blanchard (4, p.

[1] Numbers in parenthesis refer to Bibliography at end of paper.

[2] A pyroxene intermediate between diopside and hedenbergite.

429) are sparse; outcrops of unaltered salite-sphalerite ore containing 6 to 15 per cent zinc and the equivalent metore or oxidized capping [3] are common. The Pewabic mine "ore lens" ore body of low grade ore with abundant pyrrhotite has a wholly "limonitized" outcrop, different from the others. Several recently discovered ore bodies have low grade branches [4] that outcrop.

The one known case of outcropping massive sphalerite ore was overlooked until 1927. Most of the local minerals including sphalerite contain manganese and when oxidized are thinly coated with manganese oxide. Mapping on a large scale (1 in. = 30 ft.) and the systematic cracking open of all outcrops revealed the ore. Diamond drilling was used to delineate the ore body in depth.

The significance of the oxidized outcrops or gossan was recognized about 1916 by Dr. Frank L. Nason and led to the driving of an adit underneath the principal exposures of gossan. This work exposed one of the largest sulphide ore bodies known at Hanover.

Study of the gossans of the salite-sphalerite ore led to the discovery of new ore bodies in 1927. These gossans are characteristic and can be mapped even as to the former grade in zinc. The unaltered salite-sphalerite ore is composed of radiating, fibrous, Ridgway color olive 21″ o-yyn [5] salite, which usually contains several per cent of MnO,[6] as would be expected from the color (1, p. 373), and sphalerite that replaces salite as spots and patches, rarely as veinlets. Upon oxidation the texture remains unchanged (Fig. 1), but the salite breaks down to "limonite" (ochaceous orange, 15′ y-o) and manganese oxides. The "limonite" preserves the radiating fibrous structure of the salite, but the manganese migrates and precipitates as oxides that fill cracks

[3] See Locke for definitions (10, p. 4).

[4] A term proposed by the writer for low grade extensions of ore bodies upward to the surface complementing root extensions below the ore. T. M. Broderick suggests the term leakage for the same thing. Personal communication.

[5] Colors used in descriptions are Ridgway's standard (15).

[6] A complete analysis of Pewabic mine salite is given in Ref. 19. Up to 20% MnO was found in Hanover pyroxene by Charles Park (1928). Schaller calls the high manganese pyroxene johannsenite (16, p. 579).

and coat the surface with the result that the whole outcrop may in places appear blackish violet gray (59'''' m). The slightly ferriferous sphalerite (1–6 per cent Fe^{++}) breaks down to cellular "limonite" (kaiser brown, 9 or-ok) and the zinc migrates until neutralized by the neighboring limestone, where it is precipitated as the carbonate and silicate in cracks and as crusts. Some of this secondary zinc is sufficiently concentrated to make ore. When one has learned to estimate the grade of the primary ore—this can be done with an error of ± 3 per cent—the former zinc con-

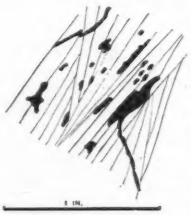


FIG. 1. Sketch of capping derived from salite-sphalerite ore, Hanover, New Mex. The texture corresponds closely with the unoxidized ore; black areas represent cellular "limonite" (kaiser brown, 9 or-ok) of former sphalerite; remaining area represents porous "limonite" (ochaceous orange, 15′ y-o) of former salite.

tent of the outcrop can be estimated closely because the textures are identical.

The examples of mineralization *leakages* above the ore bodies that occur at Hanover are perhaps the most interesting of the surface expressions. Whereas, the problems of gossans and cappings are largely ones of reconstruction of the pre-oxidation ore, these situations require structural study based on detailed mapping on scales not less than 1 in. = 100 ft. as well as study of the outcrop of the mineralization. The conditions shown by Fig. 3 are not unusual. Leakages of low grade ore (2–6 per cent Zn before oxidation) cut the younger, impure, unfavorable limestone, and connect with ore bodies below in favorable horizons. The "outcrop" is composed mainly of "limonite" and small ore bodies of zinc carbonate in the adjacent impure limestone. The ore body shown by Fig. 3 was cut by the first diamond drill

hole pointed from a mine working 300 ft. away. Success for this sort of exploration requires that the form and location of the localizing structures be known within narrow limits. Three additional ore bodies were found in similar environments and one or at most two diamond drill holes were needed for each discovery. Where no underground workings are near and the drilling must be done from the surface, the first hole is usually planned to cut a key horizon as well as to cut and fix the cross-cutting localizing structural form, such as a dike contact or a fault, as shown by Fig. 2, particularly if the horizon is deep. The

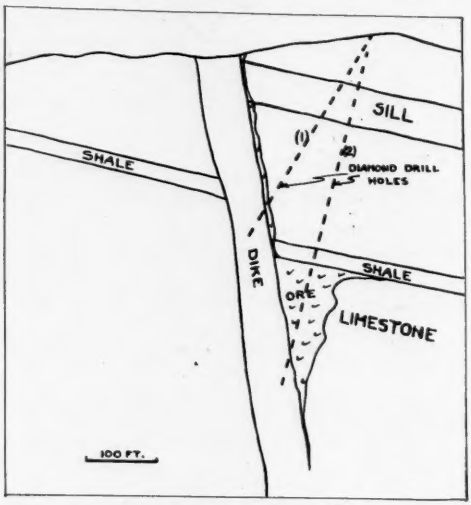


FIG. 2. Method of drilling for ore below *leakages*.

second hole in most cases should cut the favorable horizon at the critical intersection if this is not deeper than about 600 ft., when the divergence of the hole may make success uncertain. Fig. 4 is a vertical section of an ore body containing over 100,000 tons of ore that lies within a few feet of the surface. Observations of salite-sphalerite capping at " A " and a leakage or low grade gossan halo at " B " led to drilling the hole that cut the ore.

A study was made of the limestone walls near ore. The principal ore-bearing limestone is overlain first by a shale bed 18 ft. thick and then by a locally non-productive, slightly shaly limestone, 85 ft. thick. Large scale mapping (1 in. = 30 ft.) showed that the stratigraphic thickness of the limestone bed could be measured with a 5 per cent error and that this bed, when unaltered, had uniform variations in color and grain size in the direction of the stratigraphic sequence and no important variations along the strike on a given horizon. Where unaltered, the color of the bed varies through the gull grays, which are mixtures of black and white although commonly called blue in the field. The black component apparently is pigmentation largely by car-

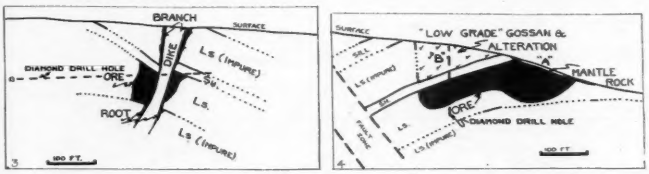


FIG. 3. Cross-section of ore with its root and branch (leakage), Thunderbolt mine, Hanover, New Mex.

FIG. 4. Cross-section of ore body with "low grade" alteration jacket, Hanover, New Mex.

bon. The wall rock alteration that accompanied the emplacement of the ore bodies resulted in decolorization possibly through the formation of white silicates from the shale particles and destruction of the carbon, and increase in grain size through recrystallization and growth of the calcite crystals. Since these alterations were difficult to recognize when mapping, special methods for measurement of the bleaching and recrystallization were tried. A color scale was selected from the series of gull grays given by Ridgway and a grain size standard made by sizing sand that was glued to cards for direct comparisons with the limestone textures. A portable cloth covered frame was made under which an operator could work in diffused light because color comparisons in the field were difficult to make in the bright sun.

Two sections of the 85 foot limestone remote from ore, one in a diamond drill hole, another in a trench, were studied with observations taken every 5 ft. stratigraphically. The data obtained were used to construct curves of color and grain size (Fig. 5);

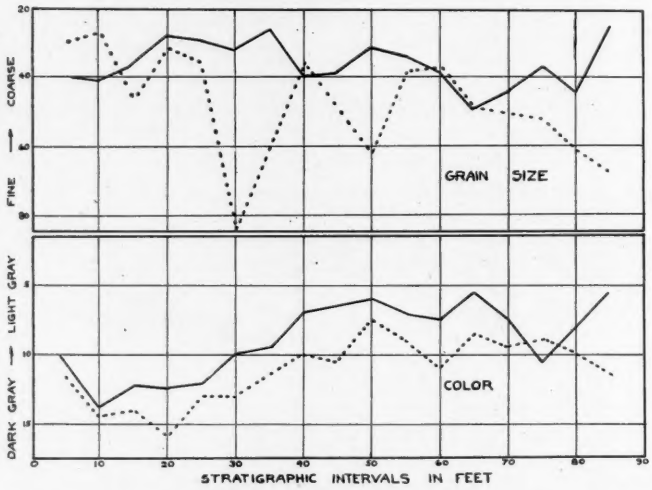


FIG. 5. Curves comparing grain size and color of a limestone bed where unaltered and where near ore. The curves for grain size are based on a standard made by gluing on cards sand sized on Tyler screens. The dotted curve is the mean of two measured on the unaltered rock sections. The solid curve is the mean of two, each of which was measured over a known ore body. The curves for color are based on the gull gray standards of Ridgway. The dotted curve is the mean of two measured on the unaltered sections noted above. The solid curve is the mean of the two measured over known ore bodies.

the ordinates express grain size or color and the abscissae stratigraphic position. Similarly two curves were constructed for the same bed with observations taken over two known ore bodies and compared with the normal curves. The comparison (Fig. 5) shows that the limestone bed over the ore was whitened and the crystals enlarged (recrystallized). Circumstances caused the

abandonment of these studies before the criteria could be used to attempt to find new ore.

At the Pewabic mine, which lies in the eastern part of the contact pyrometasomatic zone at Hanover, a prominent "limonitic" gossan occurs at the outcrop of a large lens of low grade sphalerite ore that is localized along the axial plane of an overturned syncline. The walls are silicated limestone and epidotized shale. The ore is an intimate mixture of large epidote, pyrrhotite, magnetite, salite (iron-rich pyroxene), ilvaite, and ferriferous sphalerite. The gossan is a pulverulent "limonite" with no apparent admixed silicates or magnetite. The gangue may have been decomposed by acid and ferric sulphide derived from the oxidation of the ferriferous sphalerite and the pyrrhotite, which is more than 15 per cent of the primary ore. The ilvaite, particularly, is easily decomposed by acid. A horizontal section of the ore closely duplicates the plan of the gossan. The ore was found by vertical diamond drill holes spotted down the dip from the gossan.

Vanadium, New Mexico.

The Ground Hog vein at Vanadium, New Mexico, about 3 miles southwest from Hanover and 2½ miles from Santa Rita, is a massive to disseminated pyrite, galena, sphalerite, chalcopyrite argentiferous mineralization that appears to replace gouge and breccia along a strong fault zone. No hypogene silver ore minerals are known in the ore shoots of the upper levels of the mine. Quartz and sericite are associated with the sulphides and these with pyrite predominate in the walls to about 50 feet away from the vein where they give way largely to chlorite and epidote. The structure is complicated by post-ore normal faulting with vertical throw up to 900 ft. The outcrops are an interesting case of cementation by secondary jasperoid that may be the "limonitic" jasper described by Locke (10, pp. 138–9). It is as hard as true jasper, brown to maroon in color, and looks siliceous. Since it prongs downward and terminates in supergene chalcocite and even hypogene sulphide ore, it must be supergene in nature. Some of it is confined to the outcrop in a sheet not more than 10 ft. thick; minor quantities are observed as deep as the 600 ft. level.

Under supergene conditions silica appears to have been actively taken into solution and reprecipitated, because in cavities quartz crystals averaging 1 millimeter in diameter are perched on the jasperoid, and veinlets of chalcedony cut the jasperoid (9). Besides the jasperoid, quartz and chalcedony, the outcrop contains pulverulent vermilion hematite, and orange "limonite." All of these materials are matrical to and cement an earlier breccia composed largely of grayish-white glassy quartz that is probably residual from the hypogene vein fabric. No cellular "limonite" was seen. The walls are kaolinized diorite, in places stained red with iron oxide.

Several features resulting from the supergene processes seem of special interest. First, the chalcocite ore, although it may occur from near the surface to the 450 level, in places has a cap of jasperoid that may or may not outcrop, and which is similar to that described above. This association strongly suggests a genetic relationship between the chalcocite ore and the jasperoid and should be of use in local exploration for chalcocite. Second, much of the jasperoidized outcrop, it has been discovered, is not the outcrop of the vein, but, instead, the cemented drag-ore breccia of a strike fault with 250 ft. of vertical throw. This outcrop looks identical with that of the vein proper except that breccia fragments of kaolinized porphyry in the jasperoid cement are more common. Much confusion in interpreting the structure was caused at first by the wrong identification of this outcrop, for the vein does not occur immediately below it and the faulting of the vein is not apparent at the surface.

Gilman, Colorado.

The outcrops of the massive replacement ore in dolomite at Gilman (Red Cliff district), Colorado, are found in a cliff above the Eagle river. The stratigraphic thickness of the ore-bearing bed was found to be considerably less than normal where ore outcropped or was known to occur below talus or landslide material. This became evident by a detailed mapping of the rocks exposed along the cliff on a scale of 1 in. = 100 ft.

Apparently large massive sulphide replacement ore bodies in favorable beds, overlain with weak shale that covers oxidized ore outcrops, may be revealed by accurate measurements and comparison of stratigraphic sections along the strike.

Goldfield, Nevada.

The outcrops or ledges associated with the ore at Goldfield, Nevada, are described by Ransome (13). Studies of some of the vein outcrops were made by A. Locke and the writer in 1932. The ore bodies are composed of pyrite, bismuthenite and other sulphides, and free gold in a gangue of microgranular quartz enclosed by walls of intrusive dacite and extrusive andesite. Most of the important ore is blind; only four relatively insignificant outcrops of ore were found in the principal area of the district. If erosion had stopped 100 ft. higher probably no ore would have been exposed, but if it had progressed 100 ft. deeper numerous and continuous outcrops would have been exposed. The surface is marked by numerous topographically prominent outcrops of generally barren siliceous material, which were termed ledges by Ransome. The four outcrops of ore mentioned are closely associated with these ledges and have the following features.

1. The mineral bismite (BiO) occurred within ten feet of the surface at two places.

2. The early massive quartz is shattered to a rubble breccia and gold occurs in the interspaces associated with sulphides and minor amounts of late, fine-grained, quartz. The barren ledges are unshattered.

3. They are conspicuously porous with openings up to 1 centimeter in diameter. The barren ledges are not nearly so porous.

4. Silicification is stronger than in the barren ledges and results in a glassy appearing ledge rock.

5. The areas representing the former feldspars of the altered diorite are now vugs containing second (?) generation quartz crystals; not common in the barren ledges.

6. Varicolored iron minerals such as jarosite or finely divided

hematite, are associated with the ore at the surface, but are not common in the barren ledges.

7. Second (?) generation microcrystalline quartz is common.

Little Florida Mountains Near Deming, New Mexico.

In the Little Florida Mountains near Deming, New Mexico, manganese oxides in steeply dipping fault-veins cut a country rock of volcanic agglomerate. The apex of the ore (Fig. 6) is covered by 10 to 20 feet of mantle rock that has settled into a depression, which presumably resulted from the oxidation and solution of the primary manganese carbonates and possibly also of the secondary manganese oxides in the veins. The walls are resistant and crop out so the veins are expressed at the surface by long narrow strips of talus or mantle rock. The ore was discovered by a local prospector who noted that auxiliary hanging wall fissures ended at the strip of talus. This suggested a master fissure under the talus which, coupled with the presence of some manganese float nearby, encouraged the sinking of a prospect hole in the talus. Additional manganese float was soon uncovered and solid ore was found at ten feet.

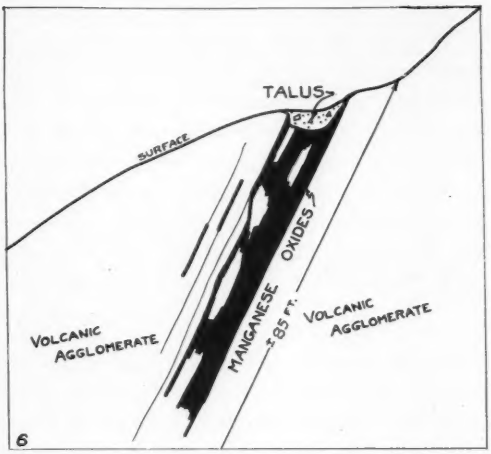
NORTHERN MEXICO.

Erupción-Ahumada, Chihuahua.

The Erupción-Ahumada, Chihuahua, manto ore shoot is enclosed by massive limestone and was found when a small surface scab of caliche about ten feet thick was broken through. Below this lay a gossan containing secondary zinc minerals.

Santa Barbara, Chihuahua.

The outcrops of the veins at Santa Barbara are among the most conspicuous known to the writer. Although the veins are massive quartz the country rock is seldom silicified so the wall-like croppings are the veins stripped bare. The primary mineralization, in addition to the predominating quartz, includes lime-iron silicates, fluorite and sulphides of zinc, lead, iron, copper, arsenic, and possibly silver, but in the outcrops all primary min-



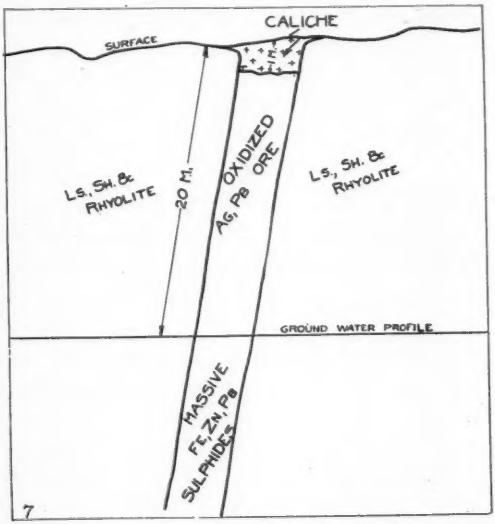


FIG. 6. Cross-section showing mantle rock covering a vein of manganese in Little Florida Mountains near Deming, New Mex.

FIG. 7. Cross-section showing caliche cap on vein at Cordero (San Juan), Chihuahua.

erals have largely disappeared except quartz. The resistance to erosion of the veins and their included ore shoots, which means the topographic prominence of the outcrops, is a rough criterion for the importance of the metallic mineralization in depth. The veins make ridges, the inter-vein areas, arroyos, and the major drainage lines mostly cross the veins where they are narrow or are intersected by post-ore cross faults. In the Hidalgo mine the widest part of the vein is also the richest (17, Fig. 6). Vein junctions are likely to be wide and rich.

Pockets and small stopes of high-grade gold ore (reported up to 80 oz. per metric ton, known up to 5–8 oz.) occur from the outcrop to about 80 feet down the dip. Although not studied in detail this ore may have been enriched both by simple gravity settling and solution of zinc and sulphur from the massive primary sulphide ore. Assays indicate that all the metals including lead, but excepting gold, are leached out for 15 to 30 feet down the dip from the outcrop. The abundant fluorite, which is closely associated with the sulphides, may have been decomposed by H_2SO_4 from oxidizing pyrite and this may have had some effect on the solution of the metals including lead which normally would not leach or migrate far. Most of the heavy metal salts of H_2SiF_6 are soluble.

Parral District, Chihuahua.

The Parral district mineralization (18, pp. 387–390) like that of Santa Barbara is chiefly early coarse quartz cut and replaced by chalcedonic quartz with which is associated contemporaneous sulphides and fluorite. The ore shoots are not largely co-extensive with the vein as at Santa Barbara, but are restricted along the strike, with the inter-shoot distances in places greater than the strike lengths of the shoots. The veins, because of the resistance of the abundant silica introduced into the fabric and walls, outcrop on the hills and ridges. Along the Veta Colorado the inter-shoot sections of the vein are loci for arroyos.

Quartz and fluorite are the only two primary minerals that remain in the outcrop without appreciable change or loss in weathering, and the fluorite, being the same age as the sulphides, is a

more exact outcrop indication for ore than the earlier quartz. The ore shoot "outcrops" also contain voids that represent the former sulphides, and some yellow oxides (?) of lead, hematite, and "limonite." All of the ore shoots in the district are expressed at the outcrop by some silver (by assay), even if blind. In searching for ore shoots a good procedure is to cut samples across the outcrop of the vein at regular intervals, in places trenching is needed, and finally to sink a prospect hole where the assays are highest, even though the silver content is below that of ore grade. Assays for fluorine should be significant.

Cordero (San Juan) District, Chihuahua.

The Codero vein outcrops are in most places capped by white caliche [7] up to 5 feet thick as shown by Fig. 7, so in plan a given outcrop appears as a narrow band of caliche bordered by limestone or rhyolite walls as the case may be. The primary ore is massive pyrite, galena, and sphalerite, which when oxidized shrinks, collapses, and results in a constricted and depressed outcrop that becomes filled with caliche. The caliche thus occurs as ribbon-like scabs covering apexes of the veins and may be derived from gypsum which in turn resulted from the attack of sulphide-derived SO_4 compounds upon the limestone and rhyolite walls. Upon weathering the gypsum is thought to be replaced largely by the less soluble $CaCO_3$.

GENERAL DISCUSSION.

This association of caliche (largely $CaCO_3$) with the oxidized outcrops of former sulphides is common in the Southwest and northern Mexico. This material has been noted at the surface in association with ore in the Silver Bell, Empire Mountains, San Xavier, and Christmas districts of Arizona; in the Hanover-Santa Rita, Organ Mountains, Silver City, and Tres Hermanas districts of New Mexico and in the Cordero and Erupción-Ahumada districts of Mexico. Some of the walls are limestone; some are less reactive rocks. In several places caliche completely covers the gossan of important ore. The explanation given for

[7] Apparently mostly $CaCO_3$, possibly some $CaSO_4$.

the Cordero occurrence may account for the genesis of most of this caliche and it may be significant that at Silver Bell, Arizona, and Goldfield, Nevada, veinlets of gypsum, in near-surface oxidized ore, merge upward into caliche caps. At the Cinco Señoras mine, Hanover, New Mexico, a caliche cap on oxidized lead-zinc ore gave the following analysis for $CaSo_4$:

	% $CaSO_4$
1. At surface	0.11
2. 0.5 ft. below surface	0.31
3. 6.0 ft. below surface	0.02

Oxidized lead and zinc ore was discovered at 8 ft. The amounts of sulphate are probably too small to be significant.

The caliche problem seems to deserve further study. When the Ahumada manto ore shoot was discovered below the caliche outcrop it was considered necessary to explore below nearly every caliche cap within a radius of several miles. The caliche cap over ore or gossan might have some peculiarity, such as a higher sulphate content, spectrographic content of metals, etc. which might aid in its recognition.

The topographic expression, positive or negative, of an *unoxidized* ore shoot is, of course, dependent on the relative resistance to erosion by the shoot and walls. A difference in resistance is the result of the many vagaries of mineralization in its effect on the veins and walls, but the type of effect may be constant for any given district thus providing a guide to the valuable mineralization. When the valuable part of the mineralization is related to a resistant gangue the rule of W. H. Emmons (7, pp. 216–217) may be useful in suggesting conditions in depth, but where the valuable mineralization is unrelated to the gangue in detail, *i.e.*, where the shoots are not closely related to resistant gangue, the rule may not be applicable. Moreover, it should be used with caution where there is a scab of resistant supergene jasperoid at the outcrop.

The positive or negative topographic expressions of *oxidized* ore shoots may present interesting cases. Probably only rarely does a positive expression arise through the concentration of "limonitic" jasperoid or ferruginous chert at the outcrop by

solution and reprecipitation, but good examples are known at Goodsprings, Nevada (8, pp. 98–99) and at the Ground Hog mine described earlier. The reason for the formation of these siliceous scabs and masses at the outcrop has been discussed by Locke (10, p. 138) and Hewitt (8, pp. 98–99). Why they are rare, and what combination of factors favors their development, seems obscure and deserves more study. They deserve careful inspection when encountered because they may replace and cover ore that otherwise would outcrop, form pseudo-vein outcrops along post-mineral faults, and cap enriched chalcocite ore. Negative topographic expression, which may be due to erosion of soft ore shoot material or to the collapse or shrinkage of the vein outcrop through oxidation and solution, is a common case and the resulting depression may be filled with caliche, mantle rock, or other material as previously discussed. The collapse or closing in of vein walls through the oxidation and solution of massive sulphide, carbonate, or other gangue and the resulting indication of ore below by thin seams with or without residual material (Kyshtim district, Russia, Locke, 10, pp. 53 and 59 after Kingsbury and Stickney) is perhaps not rare.

The recognition and study of the branch, leak, or leakage holds promise for the discovery of ore. Leakage technique has been used with success in the Central mining district, New Mexico, and one small ore body was found by its use in the Parral district of Chihuahua, Mexico, where the method, however, was not given a thorough test. Where the channelway is more or less open, hypogene mineralizing fluids appear to move chiefly upward as suggested by the general steep pitch of the ore shoots and their roots and leakages. In massive, more or less flat lying limestone that is only slightly disturbed, it is appreciated that horizontal flow—resulting in Chihuahua-type mantos—may predominate.

The usual procedure is to study the leakage expression of known ore and then to look for similar conditions in unexplored ground. Generally the leakages are expressed by alterations, "low grade" gossans, thin seams of "high grade" gossans or cappings, and residual resistant gangue minerals such as quartz,

fluorite, barite, etc. Grading into the " two dimensional " leakage is the " three dimensional " alteration jacket associated with non-outcropping or blind ore and characterized by such minerals as sericite, quartz, garnet, epidote, dolomite, primary jasperoid, tourmaline, etc. The jacket may be low-grade metallization, *i.e.*, " junore," and in places is represented by recrystallization and decolorization of colored limestone as previously described, and related changes in shales and sandstone.

It is important from a negative point of view to recognize the outcropping root of an ore body now eroded. Here the subject of the bottoms of ore shoots merges into the subject of outcrops. Since many ore shoots bottom in pyrite-bearing ground " pyrite " gossans may have special significance. The outcropping root, however, may in general be difficult to distinguish from an outcropping leakage, except where the characteristics of each are known for a given area, or where structural work shows the relationship of localizing horizons or conditions to the surface of the ground.

Structural abnormalities resulting from hypogene or supergene collapse that has reached the surface (no ore outcrops), has been recognized in a few districts (examples of hypogene subsidence: East Tintic district, North Lily mine, Paul Billingsley, oral communication; Bisbee, Arizona, Locke, 11, p. 447; example of supergene subsidence, Bisbee, Arizona, Wisser, 20).

Certain gangue or other minerals may be closely associated with ore minerals at the time of deposition and space as, for example, the fluorite at Parral, Santa Barbara and other districts and may remain in the outcrop after oxidation. In order to identify such minerals, careful studies of the primary ore with the microscope should precede extensive outcrop work.

Copper outcrop and enrichment investigators have emphasized the fact that the presence of limestone walls means rapid neutralization and where abundant may prevent enrichment, except possibly in the case of silver, which can be carried as a bicarbonate (Ravic, 14).

Silver haloids in arid and semi-arid regions commonly form rich pockets that outcrop but are shallow. AgCl seems to be

stable in $Fe_2(SO_4)_3$ and H_2SO_4 solutions (Cooke, 6) and once fixed as a haloid silver is not likely to migrate.

Galena and the oxidized lead minerals, particularly plumbojarosite, are valuable criteria of former ore because they persist in most outcrops. Galena is particularly resistant in tight rock or in large masses where enclosed in hard, resistant lead sulphate; a hammer wielded with energy may reveal it where otherwise it would be unsuspected. Rich silver ore where oxidized and leached commonly leaves copper stains at the outcrop derived from tetrahedrite, tennantite, or other silver-bearing copper minerals. Other primary ores associated with copper upon oxidation leave copper stains at the outcrop even where thoroughly weathered (Locke, 10, pp. 29–30). The quartz spectrograph may show these stains to contain considerable silver where they are derived from silver minerals, and little silver if they are residual from copper minerals.

SUMMARY AND CONCLUSIONS.

Study of certain outcrops and surface expressions of ore shoots in the Southwest and northern Mexico indicates a wide variety of occurrences and suggests the difficulty of applying empirical criteria from one district to another.

Features of outcrops apparently worthy of consideration include:

1. The cellular "limonitic" gossan previously described by Locke and others.
2. Certain significant gangue and ore minerals or their supergene modifications that are stable at the outcrop.
3. *Branches* or *leakages* produced by mineralization along outlet structural paths above ore bodies.
4. Wall rock alteration that may reveal concealed ore.
5. Surface scabs or masses of supergene "limonitic" jasperoid and caliche that may overlay ore.
6. Patches of mantle rock that may cover collapsed or eroded ore.
7. Abnormal local decreases in the stratigraphic interval that may indicate oxidation collapse of ore concealed by mantle

rock. Other structural features that indicate hypogene or supergene collapse associated with ore that never outcropped.

8. Criteria indicating that the outcrop represents the bottom of an ore shoot.
9. Structural evidence indicating that favorable horizons lie deeper, or that they have been eroded away.

Where a district has produced ore, the most effective method of outcrop study appears to be the analysis of the mined or developed ore in its geological environment, then the deductive application of the resulting information in new areas. Effective tools include: structural mapping generally by means of the plane table, qualitative and quantitative studies of the ore shoots by means of assays, thin and polished sections of the ore, and possibly the quartz spectrograph.

SILVER CITY, NEW MEXICO,
April 7, 1939.

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THE PRIMARY MINERALIZATION AT CHUQUICAMATA, CHILE, S. A.

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ABSTRACT.

The structural relations, rock alteration and sulphide mineralization of the Chuquicamata Mine are described in detail. Attention is directed to the zonal arrangement of the different types of alteration and of the sulphide mineralization.

The mineralization is associated with strong N–S fissures and several N 10° E shear zones. Several systems of tension fractures are found between these shear zones.

The host rock has the mineralogical characteristics and the chemical composition of a granodiorite. Five different types of alteration phases of this rock have been mapped. The following wallrock alteration processes have been recognized beginning with the fresh granodiorite in the eastern part of the orebody to the siliceous zone in the western part.

Enargite is the predominating primary sulphide of copper. Bornite and chalcopyrite are always present but in minute quantities. Tennantite and tetrahedrite are found in specimens from veins near the pit.

Molybdenum as molybdenite occurs in the net of quartz veinlets near the highly silicified zone. The amount of molybdenum present is very small. Most of the source of molybdenum in present workings comes from the oxide minerals such as lindgrenite and molybdenum ochres. In the course of this study the writer found a new molybdenum ochre so far undescribed in the geologic literature.

Within the orebody are bands of a fine grained rock of a texture and mineralogical composition similar to that of leucogranite porphyry.

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THE structural relations and zonal distribution determined in Chuquicamata, which are outlined in this paper, have been the outcome of the painstaking work of several geologists. Principal among these is Reno H. Sales, chief geologist for the Anaconda Copper Mining Co., whose work served as a foundation for all the work done since 1930, and Alvin V. Taylor, Jr., who in 1933 published an excellent paper on Chuquicamata, which the author has used freely in this report. To these gentlemen the writer is specially in debt for allowing the use of such information.

To the Chile Exploration Company the writer is under obligation for many fine ore specimens, maps and other data, and for permission to publish this paper.

Thanks are particularly due to D. B. Motter, Jr., assistant to the Vice-President; Reno H. Sales, Chief Geologist for the Anaconda Copper Mining Company; James Head, Chief Engineer; Burr Wheeler, General Manager of the property, and Mat Sample, Mine Superintendent, for their special interest in helping the writer in securing the material upon which this study is based.

To W. S. March, Jr., Chief Geologist of the property, and A. V. Taylor, Jr., formerly Chief Geologist, the writer is indebted for the many helpful suggestions given in the field.

The laboratory studies have been made in the Department of Geology of the Massachusetts Institute of Technology, under the supervision of Professor W. H. Newhouse. Professors W. J. Mead, H. W. Shimer, F. K. Morris and other members of the staff have been kind enough to give much advice and help in the course of this study. To these gentlemen the writer is deeply grateful.

The chemical analyses were made by Mr. W. H. Herdman of Glasgow, Scotland.

Thanks are also due to various fellow students, especially Mr. C. Frondel and Dr. C. S. Lord for friendly advice and interest.

INTRODUCTION.

It is the purpose of this paper to describe briefly the occurrence and zonal distribution of the primary mineralization at Chuquicamata, Chile.

Chuquicamata lies in the Province of Antofagasta which is located in the northern part of the Republic of Chile, between latitudes 21° to about 26° South, covering an area of 45,000 square miles (120,000 sq. km.). The Province of Antofagasta lies entirely within the Atacama desert, which is proverbial for its extreme aridity.

The geological features of Chile are geographically divided into three parts corresponding to three physiographic provinces: The Coast Range, the Valle Central and the Andes or High Cordillera.

In the Province of Antofagasta there is another physiographic unit, the Pre-Cordillera, which is a long range of mountains extending from Atacama to Tarapacá, and running parallel to the main Andean range. The Pre-Cordillera consists mainly of a mass of dioritic rocks intruded into Jurassic and Cretaceous sediments.

The copper deposit of Chuquicamata is located in the northern

part of the Province of Antofagasta, at lat. 22° 17′ S., and long. 85° 55′ W. Chuquicamata is located in the south-eastern end of the part of the Pre-Cordillera.

The present paper is the outcome of five years of field work and two years of laboratory study in the Department of Geology at the Massachusetts Institute of Technology.

In picking the samples for chemical analysis one thought was kept in mind, namely that the samples should represent as closely as possible the average composition of the rock, disregarding the material introduced as vein matter or by descending solutions along fissures, cracks, or joints. The bulk analyses then, should represent the chemical changes suffered by the host rock and in every case the gains and losses could be well determined.

STRUCTURAL FEATURES.

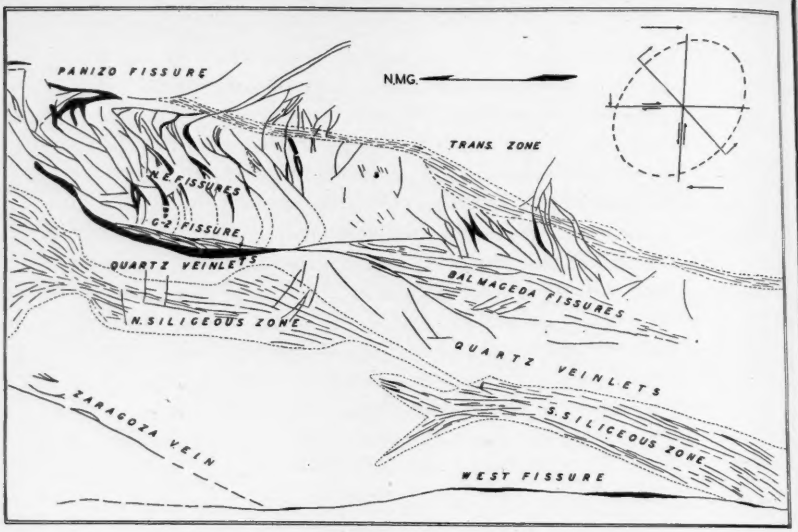
The data set forth in this part of the paper have been taken from unpublished reports of the geologists of the Anaconda Copper Mining Co., notably those of Reno H. Sales, W. S. March and M. C. Bandy and from A. V. Taylor's chapter in "The Copper Deposits of the World." To these gentlemen, the author again wishes to acknowledge his indebtedness.

The mineralized area that forms the mine of Chuquicamata lies in a crushed zone in granodiorite, between a strong fissure at the West, and a weak shear zone at the East. These zones strike in different directions; the fault zone runs north-south, and the transition or weak shear zone, approximately N 10°. Thus, in plan the mineralized zone has roughly the shape of an elongated triangle.

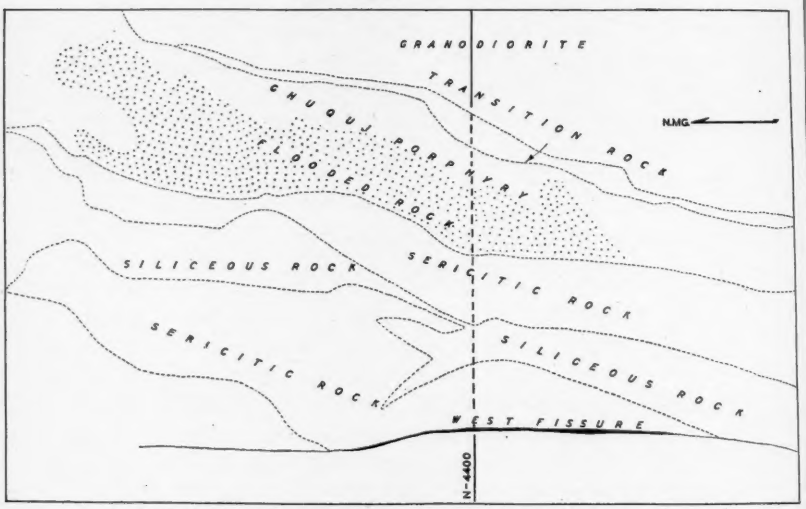
The orebody is associated with the following structural features: (Fig. 1.)

A. Structures Striking Approximately N–S to N 10° E (Shear Zones).

1. Strong North-South fault, forming the western boundary of the mine. This zone of fracture is known as the West Fissure.
2. Strong silicified zone striking about N 10° E; joins the West Fissure in the southern part of the mine. This zone has an average width of approximately 800 feet (250 meters).



1. SKETCH MAP OF THE STRUCTURAL PATTERN AT CHUQUICAMATA



2. INDEX MAP SHOWING THE GENERAL DISTRIBUTION OF THE ROCK ALTERATION

FIG. 1. Sketch map of the structural pattern at Chuquicamata.

FIG. 2. Index map showing the general distribution of the rock alteration.

3. The C–2 Fissure. This runs parallel to the northern part of the Siliceous zone. The fissure is well developed in the northern part of the mine. In the southern part it becomes less distinct and finally branches off in horse-tail fashion.
4. Strong north-south vein zone of the northeast corner of the mine. The Panizo Fissures.
5. The Transition zone, a structural continuation of the Panizo Fissures. Forms the eastern boundary of the mineralized area. The Transition zone does not form a sharp limit to the orebody, but is formed by slip planes having approximately a N 10° E direction.

B. Highly Fractured Zone Lying Between the N–S Shear Zones (Tension Fractures).

1. Between the West Fissures and Siliceous Zone.
2. Between the Siliceous Zone and the C–2 Fissure. Zone of lacing quartz veinlets.
3. Between the C–2 Fissure and the eastern boundary of the mine. The N–E Fissure and the Balmaceda Fissures. The N–E Fissure System is characterized by the curving shape of the fissure; roughly speaking, they have the form of a letter S, with the top of the S coming in contact with the Panizo Fissure and the bottom ending against the C–2 Fissure. The System of fissures forming the Balmaceda group is less conspicuous and generally they lose their characteristic S shape.

The generalized structural pattern of Chuquicamata is apparently formed by strong north-south shear zones with strong tension fractures developed between the zones.

This pattern is very suggestive of a strong shearing couple acting horizontally in a north-south direction. In Fig. 1, the suggested relation of the shear zones and tension fractures to an ellipse of strain is diagrammatically expressed. The ellipse is oriented essentially parallel to the fracture system in the map.

ROCK ALTERATION.

Classification and Distribution.—Actually, the sheared granodiorite, east of the "West Fissure," is what constitutes the mine. Within this fractured zone several alteration phases of the granodiorite occur. These different types of alteration occur in roughly parallel bands running approximately N 10° E (Fig. 2).

From east to west, from the fresh granodiorite to the West Fissure, the following zones have been mapped.

Zone *	*Type of Alteration*
1. Fresh granodiorite	Rock somewhat epidotized near the Transition Rock.
2. Transition	Chloritization and some albitization.
3. Chuqui Porphyry	Albitization and some sericitization
4. Flooded Rock	Sericitization and some silicification.
5. Sericitic Rock	Complete sericitization and quartz veinlets.
6. Siliceous Rock	Intense silicification.
7. Sericitic Rock	Same type of alteration as shown by Zone No. 5.

Chuqui Granodiorite.—This forms the eastern boundary of the mine. In hand specimens it is a medium grained rock of light gray to greenish-gray color. The grain size of the feldspar and ferromagnesian minerals ranges between 2 and 6 mm. Under the microscope the texture is typically hypidiomorphic (Fig. 3). The soda lime feldspar is mostly partly idiomorphic; euhedral and subhedral biotite and hornblende occur. These minerals are generally cemented by a mass of perthitic orthoclase and quartz, which is quantitatively speaking rather variable, being abundant in some phases and inconspicuous or absent in others.

The plagioclase feldspar is of the oligoclase variety although albite also occurs (Fig. 8). The chemical composition of this rock is given in Table 1. The mineralogical composition based on the recast of the chemical analysis and microscopic study is given in Table 2.

Transition Rock.—Forming the eastern boundary of the mine is a zone of weakly sheared and altered granodiorite known as the Transition Rock. This zone varies from less than 10 meters to about twenty-five meters or more in width. In hand specimens it resembles the fresh granodiorite as to texture and mineralogical composition. The occurrence of specular hematite in thin seams and stringers imparts to the rock a dark color. The

* Local names given to the different zones; they are, properly speaking, alteration phases of the same rock: the Chuqui Granodiorite.

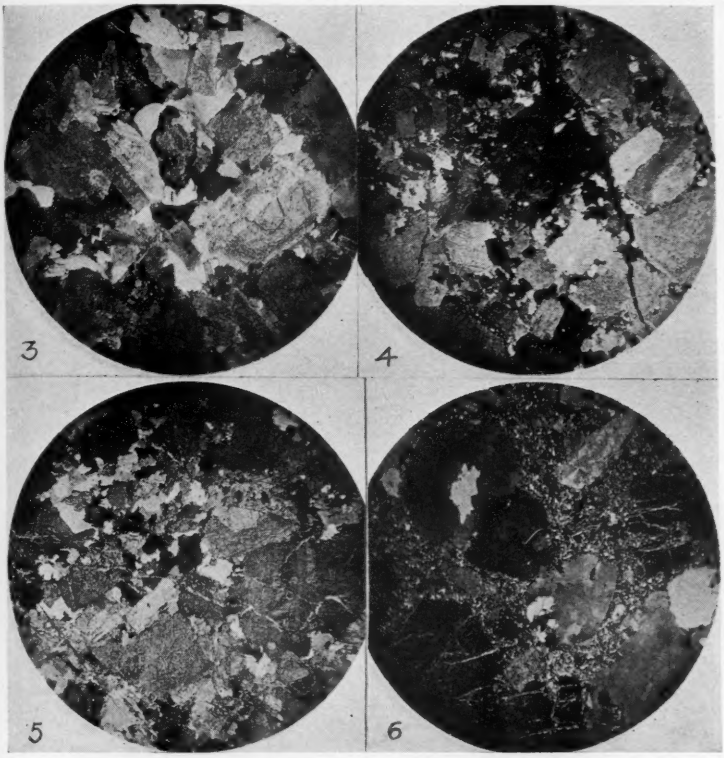


FIG. 3. Texture of the Chuqui granodiorite; note hypidiomorphic character of the feldspar. Feldspar altering slightly to sericite. X-nicols, × 8.

FIG. 4. Transition Rock; shows same textural character as granodiorite. Chlorite (Ch) replaces biotite; magnetite (mg) formed along former cleavage lines of biotite. Small quartz grains (qt) developed near feldspars. X-nicols, × 8.

FIG. 5. Chuqui-Porphyry; note same textural character of the granodiorite. There is more granular quartz developed in borders of feldspar, which shows greater alteration. X-nicols, × 8.

FIG. 6. Chuqui-Porphyry showing augen structure (quartz-eyes). X-nicols, × 8.

TABLE 1.

CHEMICAL ANALYSIS OF THE GRANODIORITE AND ALTERATION PHASES COMPARED WITH THE CHEMICAL ANALYSIS OF THE ALTERED PHASE OF THE PORCELAIN ROCK.

	1 Fresh Grano-diorite	2 Trans. Rock	3 Chuqui Porph.	4 Flooded Rock	5 Seric. Rock	6 Silic. Rock	7 Porc. Rock
SiO_2	66.92	69.88	70.40	66.98	76.55	70.15	60.2
Al_2O_3	16.08	15.94	14.53	15.86	10.21	14.07	14.52
Fe_2O_3	1.38	.51	Tr.	.63	Tr.	.67	Tr.
FeO	2.22	2.21	1.36	.37	1.40	1.27	2.37
MgO	1.44	.54	.33	.35	.18	.35	.36
CaO	2.93	.90	.56	1.18	.64	.63	.94
Na_2O	4.34	5.77	2.48	.38	.42	.29	1.22
K_2O	2.38	2.26	5.04	4.66	5.06	5.66	4.23
H_2O-	.55	.35	.35	.35	.20	.35	.80
H_2O+	1.40	1.20	2.40	3.05	2.70	4.00	7.15
TiO_2	.18	.09	.10	.05	.04	.09	.14
P_2O_5	.14	.09	Tr.	—	.14	Tr.	—
CO_2	—	—	—	—	—	—	—
S	—	.22	.30	.34	.27	—	.50
SO_3	.07	.17	.86	1.14	1.13	1.34	2.88
FeS_2	—	—	.22	3.07	.18	.98	2.49
Cu	—	—	1.10	1.29	1.11	—	2.05
MnO	—	—	—	—	—	—	—
Total	100.03	100.13	100.03	99.70	100.23	99.85	99.85
Sp. Gr.	2.74	2.71	2.67	2.84	2.73	2.74	2.71

TABLE 2.

APPROXIMATE MINERAL COMPOSITION OF THE GRANODIORITE AND THE DIFFERENT ALTERATION PHASES.

Mineral	1 Fresh Rock	2 Trans. Rock	3 Chuqui Porph.	4 Flooded Rock	5 Sericitic Rock	6 Siliceous Rock
Quartz	25.30	24.18	32.20	43.00	62.00	65.00
Orthoclase	10.20	10.00	26.70	10.20	4.00	5.00
Albite	37.25	48.80	21.10	3.25	—	—
Anorthite	12.90	3.62	2.45	5.75	—	—
Biotite	8.10	—	—	—	—	—
Iron Ores	1.45	1.22	.85	.65	—	—
Apatite	.35	.21	—	—	—	—
Titanite	.45	.22	.25	.15	—	—
Chlorite	2.75	4.56	1.90	1.70	—	—
Sericite	—	4.65	4.60	25.10	28.00	20.00
Kaolin	1.25	2.03	6.60	3.50	3.50*	10.00*
$CuSO_4$	—	.61	2.75	2.60	2.50	—
CuS	—	—	.35	1.00	—	—
Pyrite	—	—	.22	3.10	—	—
Total	100.00	100.00	100.00	100.00	100.00	100.00

* Kaolin, jarosite, limonite and other supergene products recast under one figure.

chloritization of all ferromagnesian minerals gives a greenish tint to the rock. In thin section the rock exhibits the same textural habit as the granodiorite (Fig. 4). It differs from this rock, however, by the existence of specular hematite in veinlets cutting the feldspars and quartz, and by the ferromagnesian minerals having been completely altered to an aggregated chloritic mass. The chemical analysis and mineralogical composition are given in Tables 1 and 2.

Chuqui Porphyry.—In hand specimen this phase of the alteration of the granodiorite exhibits a porphyritic texture caused by the presence of large orthoclase phenocrysts (Fig. 5) and large quartz grains. These quartz grains are locally known as "quartz eyes" because in places they have an elongated lens-like pseudocrystalline outline (Fig. 6). The groundmass of the rock is composed of small plagioclase crystals cemented by quartz and orthoclase. The chemical and mineralogical composition is given in Tables 1 and 2.

Intense albitization is the prominent feature of this rock. The disappearance of ferromagnesian minerals including chlorite is another feature of interest. A marked increase in silica is shown by the development of quartz eyes and quartz veinlets.

Flooded Rock.—Megascopically this phase of the alteration resembles the phase described above, the Chuqui Porphyry. It differs from it, however, in the amount of quartz and sulphide minerals present. These minerals impart to the rock a grayish color as contrasted with the albitic white of the Chuqui Porphyry (Fig. 7). The chemical and mineralogical composition is given in Tables 1 and 2.

The rock shows more alteration than has been hereto described. It shows an increase in silica and potash and a decrease in soda, magnesia and lime, which, mineralogically speaking, is reflected in the larger amount of quartz and sericite found with the practical absence of soda-lime and magnesia-bearing minerals (Fig. 6). Cataclastic features abound and are somewhat stronger in character.

Sericitic Rock.—The material typical of this zone, in hand specimens, is a fine sericitic aggregate of white color and silky

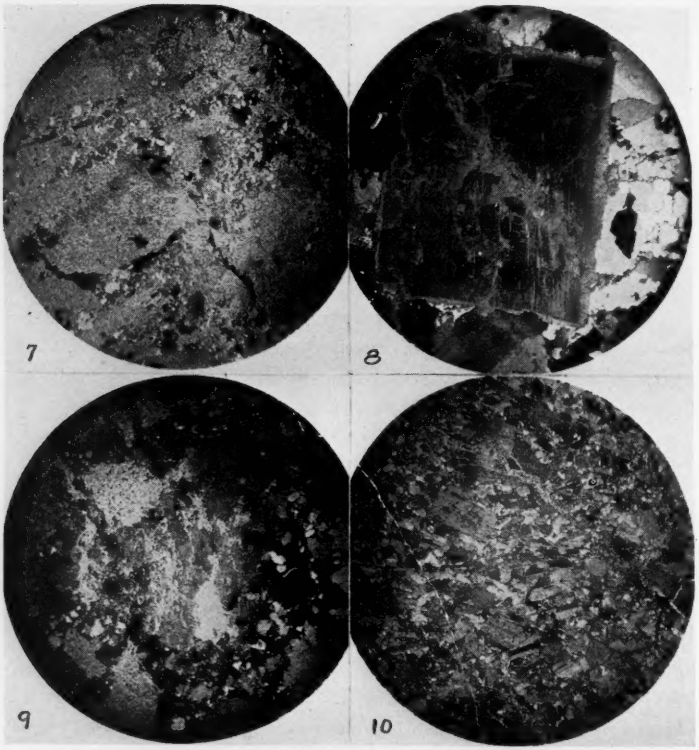


FIG. 7. Flooded rock; shows greater alteration of feldspar, but outlines are still preserved. Note sulphide veinlets and aggregated character of the quartz. X-nicols, × 8.

FIG. 8. Crystal of plagioclase in fresh granodiorite cut by veinlet of albite. Note also the rim of clear albite surrounding it. X-nicols, × 25.

FIG. 9. Sericitic Rock showing sericite veinlets cutting large crystal of orthoclase. X-nicols, × 8.

FIG. 10. Fresh phase of the Porcelain Rock; note porphyritic habit and arrangement of the small crystals forming the groundmass. X-nicols, × 8.

luster. In places this aggregate is cut by fine quartz veinlets. The copper sulphates impart to some specimens a light green color. The chemical and mineralogical composition is given in Tables 1 and 2.

The alteration suffered by the granodiorite in this zone, has caused the complete sericitization (Fig. 9) and silicification of the feldspars, plagioclase and orthoclase, with obliteration of the original texture. The rock consists mostly of quartz and sericite with minor amounts of introduced substances of supergene origin. The rock also shows a greater amount of dynamic deformation, which has produced and developed all sorts of cataclastic structures.

Siliceous Rock.—This rock, in hand specimens, is composed wholly of quartz with minor amounts of sericite. The chemical analysis of this type of rock given in Table 1 was made from an intermediate type of siliceous rock. The higher siliceous phase proved under the microscope to be nearly 95 per cent quartz or more. The mineralogical recast given in Table 2 is based on the analysis of the intermediate type. The most prominent feature of this zone is the complete silicification of the rock, with a total loss of the original texture and constituents with the exception of silica. Cataclastic features are very pronounced.

THEORETICAL CONSIDERATIONS OF ROCK ALTERATION.

In the preceding paragraphs a general discussion of each phase of the rock alteration was made. In the following paragraphs these changes are brought together to show the gradation existing from the fresh granodiorite to the highly siliceous zone.

Changes in Microscopic Features.

Textural Character.—In the description of the granodiorite the hypidiomorphic texture of the rock and its phorphyritic habit were noted. This texture has been preserved throughout the different phases of alteration, becoming less and less conspicuous toward the Siliceous Zone, where it becomes obliterated by the complete silicification of the rock. In the intermediate phases, the hypidio-

morphic character of the plagioclase feldspar has been preserved by the aggregate of replacing minerals.

The persistence of the original texture seems to point toward one original rock, which was altered after consolidation. The texture exhibited throughout resembles that of the fresh granodiorite.

Cataclastic Features.—Under the microscope the study of the several phases of alteration shows a variation in the cataclastic features from one phase to the other. These variations indicate an increase in deformation reaching a maximum in the siliceous and immediate zones.

Chemical Changes.

Inspection of the analyses of the different types of alteration at Chuquicamata shows that the process of alteration has changed very markedly the relative amounts of the different constituents. The change in composition is due to the addition of certain components and removal of certain other substances. In order to show in a specific manner the nature of these changes, two types of diagram were constructed:

1. Composite straight line diagram. This diagram shows graphically the relative change of one substance in the different phases of rock alteration as compared with the fresh granodiorite taken as standard. (Fig. 11.)

2. Variation diagram along a section of the mine. This type of diagram illustrates the changes in composition of the different types of rock alteration along a section of the mine taken approximately at Coordinate N–4400. The construction of this diagram is self explanatory. (Figs. 12, 13.)

Each of the diagrams has a different purpose; the straight line diagram gives relative changes from the granodiorite; the variation diagram shows these changes have taken place from the granodiorite to the siliceous rock.

Changes in SiO_2 Content.—The straight line diagram shows that the amount of silica increases from the fresh granodiorite to the siliceous rock. It shows, moreover, that the amount gained

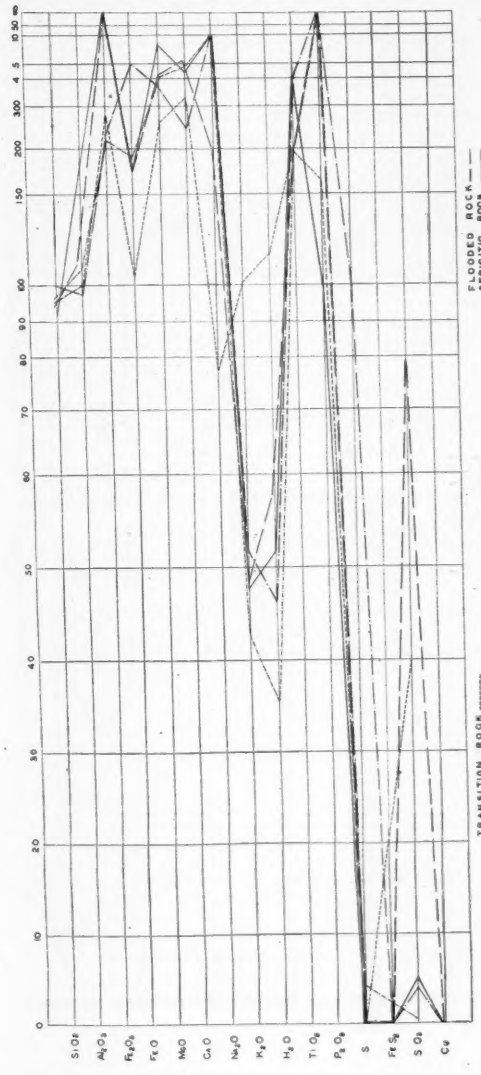


FIG. 11. Composite straight line diagram showing relative chemical changes in altered rocks as compared with fresh granodiorite.

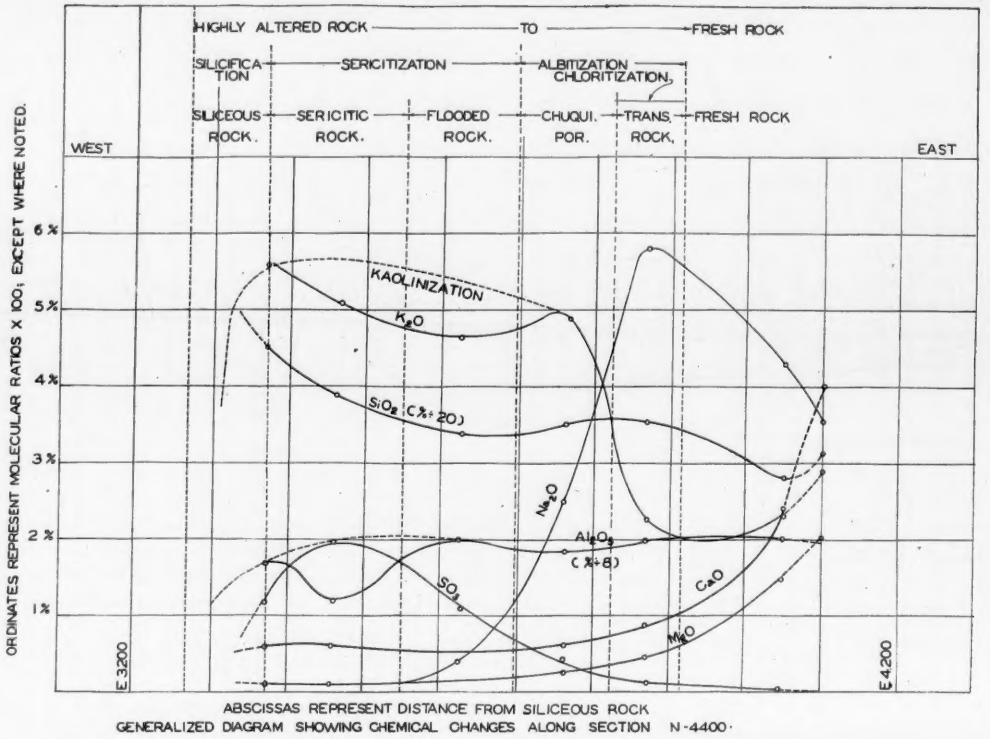


FIG. 12. Generalized diagram showing chemical changes along Section N–4400.

HIGHLY ALTERED ROCK — TO — FRESH ROCK
SILICIFICA — SERICITIZATION — ALBITIZATION CHLORITIZATION

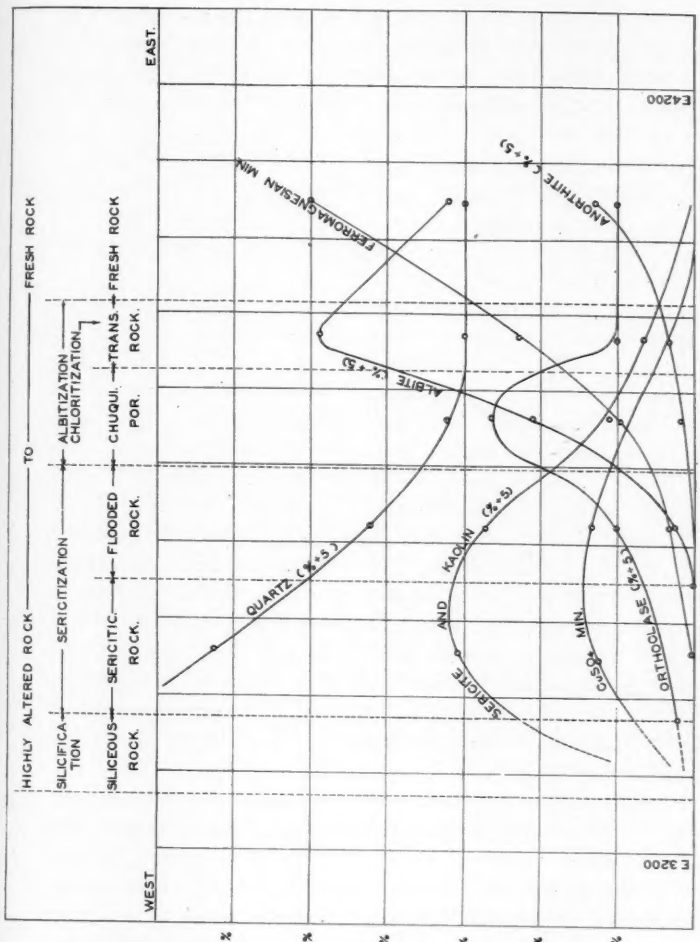


FIG. 13. Generalized diagram showing mineralogic changes along Section N-4400.

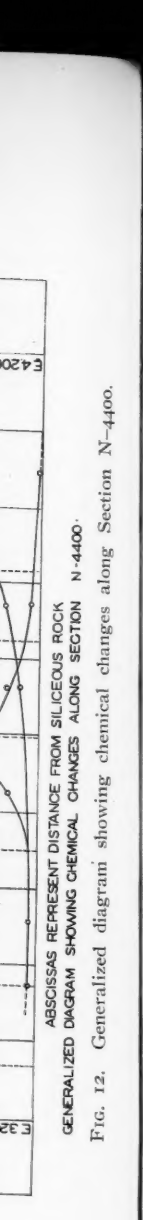

E4200
ABSCISSAS REPRESENT DISTANCE FROM SILICEOUS ROCK
GENERALIZED DIAGRAM SHOWING CHEMICAL CHANGES ALONG SECTION N-4400.

FIG. 12. Generalized diagram showing chemical changes along Section N-4400.

is practically constant in the intermediate phase of alteration and increases rapidly in the sericitic and siliceous phase. These facts are also shown in the variation diagram by the curves formed by the silica points. This curve turns toward a maximum in the siliceous zone and a minimum in the fresh granodiorite; between the two the curve passes through a transition period in which it almost becomes a straight line. These show that the amount of silica present in these zones is practically equal. The projection of the SiO_2 line toward a hypothetically average granodiorite shows that the so-called fresh granodiorite of Chuqui is slightly higher in SiO_2 than the normal rock.

Changes in Al_2O_3.—In general, the straight line diagram shows a relative loss of alumina throughout all the phases of alteration. The loss is not large but enough to be noticeable. The maximum relative loss is reached in the Sericitic Zone, from this zone toward the fresh granodiorite the loss of this constituent is practically negligible and it may be said that it has remained constant. The projection of the Al_2O_3 curves in the variation diagram toward the hypothetical granodiorite average shows the amount of Al_2O_3 to be equal or nearly so, and therefore to have remained constant.

Iron Oxides.—The presence of a certain amount of limonitic material in all the phases of rock alteration and of introduced specular hematite in the Transition Rock makes the study of the changes in primary ferrous and ferric iron somewhat difficult. However, the changes as illustrated by the straight line diagram, and aided by microscopical studies, show a complete removal of these substances as primary constituents from the granodiorite toward the Siliceous rock.

Changes in MgO and CaO.—Magnesia and lime behave in very much the same way and, therefore, a general discussion will apply for both.

The relative loss of these substances increases from the fresh granodiorite toward the more altered phases. These facts are indicated by the behaviour of the points marking the relative loss in each phase, these points tending to move progressively right as the grade of alteration increases. In the variation diagram these facts are shown by the regular behaviour of the curves,

which may be interpreted as being due to a complete removal of these substances by the incoming solutions.

The projection of the curves of lime and magnesia in the variation diagram shows that the fresh phase of the granodiorite near the orebody is lower in those constituents than the average rock of the same type.

Changes in Na_2O.—Soda behaves differently from any other substance so far described. From the straight line diagram it can be seen that there is a distinctive increase of this substance in the Transition phase, and there is a gradational loss in the other phases. The siliceous rock shows almost a complete loss of this constituent. These same facts are revealed in the variation diagram; here, however, the increase in soda occurs in the outer rim of the ore deposit. The analysis of the Chuqui granodiorite shows also a larger amount of Na_2O than the average granodiorite.

Changes in K_2O.—The potash behaves most peculiarly. As a whole there is a gain of this substance except in the Transition phase; here the amount of potash is somewhat below normal The fresh granodiorite shows also a lack of this substance.

In the variation diagram the behaviour of potash resembles generally that of alumina. From the Chuqui granodiorite to the Transition rock there is a slight change in the potash content. From the Transition to the Siliceous zones there is a marked increase; however, between these two points the curve shows a minimum indicating that the amount of potash becomes smaller in the sericitic area. This loss can be accounted for by the removal of these materials by supergene solution. The mineralogical changes that this subtraction entails will be discussed under the mineralogic changes of the phases.

Changes in H_2O.—There is a gain in water in all phases. Some of this water is of supergene origin and, therefore, a complete discussion cannot be given here. Mineralogical evidences, however, point toward an enrichment in water due to hypogene solutions.

Minor Constituents.—The straight line diagram shows a pro-

gressive removal of titanium and phosphorus from the fresh rock toward the siliceous rock.

Other Substances.—The straight line diagram shows a gain in sulphur, copper and pyrite. Part of these substances are of hydrothermal character and part of supergene origin. The relative gains, induced by hydrothermal solutions, therefore, cannot be discussed. It is, however, worth noting the concentration of sulphur as SO_3 in the Sericitic zone. This fact will be mentioned again in the general discussion of the distribution of copper oxides.

Mineralogical Changes.

The mineralogical composition of the different alteration phases, as calculated from the respective chemical analysis is given in Table 2.

This table serves as a base for the variation mineralogic diagram (Fig. 13). This diagram gives the quantitive mineralogic changes along Section N–4400. It brings out, moreover, the outstanding mineralogic features that characterize each phase of the alteration. The following paragraphs discuss the variation change of each of the minerals, along this section.

Quartz.—Silica as quartz behaves differently from SiO_2. The amount of quartz varies slightly from the fresh granodiorite to the Chuqui Porphyry. The curve representing quartz through these phases is practically flat. From the Chuqui Porphyry toward the siliceous rock, the curve changes in character and becomes steep denoting a decided increase in quartz. This increase is noticeable in the Flooded Rock and extremely marked in the Sericitic Zone. The Siliceous Zone is composed almost entirely of quartz.

Orthoclase.—Orthoclase and quartz are the only two persistent minerals. They occur in practically all of the different phases of alteration.

From the fresh granodiorite through the Transition Rock there is apparently no gain in orthoclase. The amount of orthoclase increases through the Chuqui Porphyry and declines again toward the more altered phases. The amount of orthoclase present in

the Flooded Rock is practically equal to the amount existing in the Fresh Rock; the amount present in the Sericitic Rock is somewhat lower. Through the Sericitic Zone the amount of fresh orthoclase declines and becomes negligible as the Silicified Zone is approached.

Plagioclase.—In the fresh granodiorite the greater part of the plagioclase present has the composition of oligoclase. However, for the purpose of discussion, the amount of lime and soda entering in the composition of the plagioclase have been recast as anorthite and albite. This treatment has the advantage of showing the behaviour of the two molecules, the impoverishment of the anorthite from the Fresh toward the Siliceous Rock and the enrichment of albite in the phases adjoining the Fresh Rock. The curves show that these two molecules behave differently, and that there is a tendency for the plagioclase of the Transition Rock and Chuqui Porphyry to approach the acid end of the series and to become nearly albitic in composition.

(*a*) *Anorthite.*—A glance at the curve shows a progressive removal of this substance from the fresh granodiorite to the more highly altered phases.

(*b*) *Albite.*—The albite curve shows that there has been an enrichment of this substance in the phases adjoining the Fresh Granodiorite, the Transition and the Chuqui Porphyry. Beyond these phases toward the Siliceous Rock, the amount of albite decreases rapidly and disappears completely in the Sericitic Zone. It is worth noting here its local concentration along the outer borders of alteration.

Biotite and other Ferromagnesian Minerals.—In the detailed description of the different phases of the alteration attention has been called to the complete chloritization of the fresh ferromagnesian minerals in the zone adjoining the Fresh Granodiorite, the Transition Rock. This chloritization is progressive in nature; it shows that the ferromagnesian minerals have been the first to be attacked by the incoming solution.

The relationship between the chlorite and fresh ferromagnesian minerals is so close that the quantitative changes had to be considered together. The curve representing the ferromagnesian

minerals is similar in nature to the anorthite curve; both show a progressive decline from the Fresh zone to the Siliceous, disappearing before the higher altered phases have been reached.

Iron Ores.—No quantitative study has been made because of the presence of limonite and other iron-bearing minerals of supergene origin. Microscopically, however, it can be said that iron ore as a primary constituent of the granodiorite class disappears rapidly toward the more altered phase, and behaves much in the same manner as the ferromagnesian minerals.

Sericite.—Sericitization abounds through all the phases of alteration, even the fresh granodiorite showing a certain amount. However, the quantitative study shows that there is a progressive gain in sèricite from the fresh rock to the siliceous rock. This gain reaches its maximum along the Sericitic Zone and declines sharply as silicification becomes more intense.

Kaolin and other minerals due to weathering processes vary proportionally to the sericite present. Kaolinization reaches its maximum along the more sericitic zones.

Alteration Processes and Paragenesis.

All the evidence cited—field, microscopic, and chemical—are believed to point toward a continuous and complex history in the development of this deposit.

The occurrence of large quantities of orthoclase, perthite and myrmekite, as late magmatic products, indicates that the history began right after the consolidation of the granodiorite was complete, or at a very late stage in the consolidation. Ross [1] says:

> Potassium feldspar is normally a late mineral in the course of crystallization of igneous rocks, but even later albitic rims, myrmekite or albitic micrographic quartz may develop: processes that belong to a very late or even deuteric stage of crystallization. Schaller's [2] study of pegmatites has shown that where albite is present it is invariably the result of secondary hydrothermal replacement of the original potassium feldspar. By this method potassium is extracted from the parent igneous rock, or from pegmatite apophyses, and is available to form potassic minerals (principally sericite) as the solution escapes. Thus albitization, sericitization and probably the development of alunite that are so extensive

[1] Ore Deposits of the Western States. A. I. M. E., Lindgren Vol., p. 135.

[2] Ore Deposits of the Western States. A. I. M. E., Lindgren Vol., p. 144.

in connection with many ore deposits, are all related processes, which are the result of alkali rich emanation during a very late stage in the crystallization of a magma.

In thin sections the deuteric potash-feldspar shows signs of brecciation and cutting by veinlets of sericite, quartz and sulphides and indicates that the process continued from the deuteric through the hydrothermal stage.

Where orthoclase is invaded, the sericite is observed to form first along fractures, cleavage planes or other obvious channels.

The rock alteration at Chuquicamata is intimately related with the structural pattern. It seems that the controlling features are the N 10° E shear zones and the tensional fractures developed between them (Figs. 1 and 2).

The increase in the intensity of alteration from east to west points toward the western boundary as the source of solution. The geological sections suggest that the West Fissure (probably the strongest fractures) tapped the magmatic reservoir containing the mineralizing solutions. These solutions probably diverged when encountering the shear zones that to-day form the Siliceous and other zones.

The zonal arrangement existing at Chuquicamata shows that quartz and sericite predominate near the most altered zone, and albite, chlorite and epidote away from this zone in the mentioned order. This gradational change in alteration suggests that the intervening rocks have acted as a screen or filter, changing the nature of the solutions penetrating into the rock from the main channel.

Sericite forms easily and abundantly from potash feldspar. It also forms from oligoclase and andesine if the replacing solutions are rich in potassium. The potassium contained in the solution changes the sodic silicates into potassic silicates, which unite with aluminum silicate to form sericite. This will result in a progressive elimination of soda and introduction of potash. The deposition of soda then as an outer ring in the orebody may be due not to absence of potash in the solutions but to the stability ranges of the feldspars, albite being the stable one at low temperatures. In other words, it is suggested here that the introduction of

potash that formed the sericite caused the soda to migrate outward to form the outer rim. This antipathetic relation of soda and potash is illustrated in Fig. 14 where potash and soda (as percentage) in the different alteration phases, are plotted with the K_2O : Na_2O ratios as abscissae. The antipathy of the potash and soda is well brought out, but although this feature is general, it must be observed that the actual curves are valid only for the

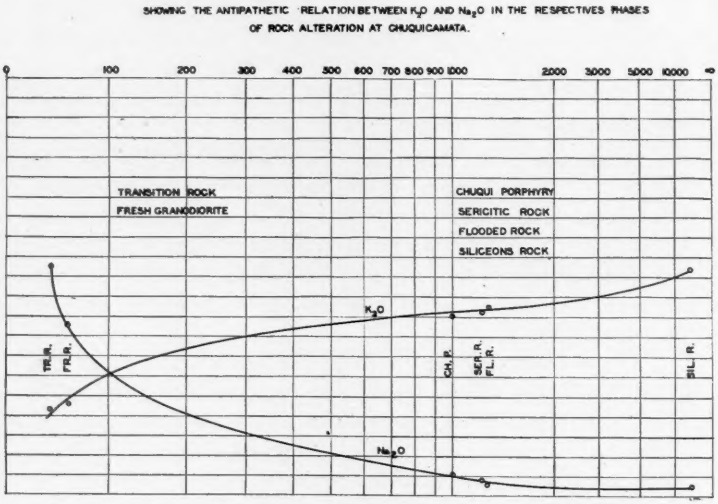


FIG. 14. Antipathetic relation between K_2O and Na_2O in the respective phases of rock alteration at Chuquicamata.

alteration phases at Chuquicamata, which evidently constitute a simple serially related group.

The mineral alteration in the chlorite phase, outside of the albitic phase, requires certain chemical readjustment. The passage of amphibole and biotite to chlorite requires the addition of water and separation of silica. The mineral association seems to indicate that the solutions here were not strongly alkaline, as it has been advocated, because chlorite probably cannot be formed under the influence of strong alkaline solutions.

The changes suffered in the epidotic zone require certain changes in the solution. With respect to the replacement of ferromagnesian minerals by epidote and chlorite, there is probably a mere recombination of the bases, lime and potash. Possibly sufficient lime may be furnished by the hornblende, but there is a greater possibility that portions of this base would come from the oligoclase in the other zones, especially since this mineral is giving place to appreciable amounts of sericite. As epidote contains much ferric oxide, it seems that the solutions, by the time they reached this zone, had lost their reducing action, but this does not necessarily imply that epidote must have been formed under oxidizing conditions.

The general relations of quartz as a primary constituent of the granodiorite and the general relation of secondary introduced hypogene quartz to orthoclase, sericite and sulphides, seems to indicate that silica was a dominant component of the mineralizing solutions. The silica was probably kept in solution by the presence of potash and soda. The work of Morey [3] shows that alkalies are a most efficient agent in promoting the solution of silica. Field relations aided by microscopic studies indicate that the bulk of the silica was probably introduced along with the potash-rich solutions that sericitized the country rock, or somewhat later, but preceded the sulphides. A certain amount of silica accompanied the sulphide.

The following relations between sulphides and sericite have been taken as suggesting a later age for the sulphides: Sulphide veinlets cut across completely sericitized plagioclase; fine laths of sericite are included in the sulphides, generally near the edges, less commonly in the rims of the grains. This occurrence may be considered to be inclusions of sericite in the sulphides.

Some of the pyrite bears no relation to the sulphide veinlets; moreover, in extreme cases the grains of pyrite are in places associated with traces of ferromagnesian minerals entirely isolated from any channels of circulation. Such relations are suggestive of the formation of pyrite from ferric minerals by the

[3] Morey, S. W.: The development of pressure in magma as a result of crystallization. Jour. Wash. Acad. Sci., 12: 225, 1922.

addition of sulphur to the iron contained therein. Pyrite also occurs in granular form, as anhedral particles, thus differing from the characteristic crystal forms that are so common in veinlets and veins of sulphides. This suggests that pyritization took place in different stages; in the early stage sulphur combined with the iron of the ferromagnesian to form pyrite, in the second stage introduction of both iron and sulphur replaced minerals indiscriminately.

The early pyritization of the ferromagnesian minerals indicates that sulphur was introduced as hydrogen sulphide, elemental sulphur or potassium sulphide. The process may mean also deoxidation of iron and development of sulphur dioxide. It seems unnecessary to suppose that sulphur was the only reducing agent present.

Summary of the Study of Rock Alteration.

The deuteric phase of the cooling granodiorite was followed by a hydrothermal phase that completely altered the essential constituents of the original rock as follows: The ferromagnesian minerals and iron ores were attacked first, passing through the preliminary chloritic-epidotic to a sericitic state. Kirk [4] speaking about Butte, says:

> When this transformation is well begun, plagioclase begins to pass over into sericite and secondary silica and the commencement of this alteration is followed by the more direct passage of orthoclase into the same two minerals. At this stage zoisite is well detected while epidote has well disappeared. Possibly paragonite occurs in traces, but it was not identified with certainty; *soda* indeed seems not to have been needed by minerals developing under the existing conditions, and was therefore *eliminated* from the rock. Primary quartz gives place in a large degree to the invasions of sericite. But for its small amount and questionably accurate determination by any quantitative method, the persistent one fourth per cent volume of titanic acid, existing finally as rutile might well be used as a criterion of constancy of other minerals during these alterations. Thus the two stages of hydrothermal alteration are seen to pass into each other very gradually, and while certain index minerals give evidence of differences in intensity of alteration at different times, the general nature of the activities have been much the same throughout. The terms chloritic and sericitic become therefore phasal distinctions, referring rather to resulting products than to material change in processes.

[4] Kirk, C. T.: Condition of mineralization in the copper veins at Butte, Mont. ECON. GEOL., 7: 35–85, 1912.

The same discussion may be applied to Chuquicamata except that in Chuquicamata there is an intermediate stage between the chloritic and sericitic phases represented by complete albitization. In Chuquicamata the soda is not lost, it only has migrated to a lower temperature zone. In the same way some of the lime and magnesia has migrated from these phases to the chloritic and epidotic phases.

This leads to the final conclusion of Kirk quoted above.

Conclusions on the Study of Rock Alteration.

The conclusions derived from the study of rock alteration are as follows:

1. Zonal distribution of the different phases of rock alteration parallel to the main shear zones. These zones varying in extent and intensity of the alteration.
2. Different phases, epidotic, chloritic, albitic, sericitic and siliceous are phasal distinctions, referring rather to resulting products than to material processes.
3. The most prominent process is the progressive elimination of soda lime, magnesia and concentration of potash and silica. The concentration of potash is closely connected with the formation of sericite.
4. The most prominent minerals formed by the metamorphic processes are potassium mica (sericite) and quartz.
5. The alteration consists in the total or partial loss of certain constituents and the gain of others and the introduction of new compounds and elements.
6. The intensity of the process observed indicates that the incoming solutions acted under moderately high temperature and pressure, probably within the range of the mesothermal deposits of Lindgren.

PORCELAIN ROCK.

Within the orebody there is a fine-grained rock of hypabyssal character.

Occurrence.—Little is known as to the general distribution of

this rock in the orebody. It occurs along the "Flooded Zone" and has been mapped as an integral part of it. Taylor, discussing this rock, states:[5] "One type of this rock (the Flooded Rock) has been locally named *Porcelain Rock*, as it resembles porcelain substance. It is very fine grained and is composed of quartz, sericite and residual feldspar."

The location of the typical hand specimens submitted for study showed when plotted on the map, that the outcrops from which they were selected flank the eastern side of the "Flooded Zone," and moreover, shows that their alignment has a N 10° E trend, indicating a parallelism in its occurrence to the main structural features and alteration bands of the orebody. The writer recalls that the Porcelain Rock occurs in bands approximately of 100 to 150 feet in width (50 meters).

Chemical Composition.—Table 1 shows the chemical analysis of a single sample of altered Porcelain Rock as it compares with the analysis of the granodiorite and its alteration phases. It shows at a glance that this rock has suffered different changes through the alteration processes acting upon it. This can be ascribed only to a different original composition.

Megascopic Features.—In hand specimens the rock seems to be composed of a fine-grained, dense, white ground mass with scattered medium size phenocrysts of quartz and orthoclase. The ground mass is so fine that it gives to the rock a porcelain-like texture.

Microscopic Features.—Under the microscope, in thin sections, the Porcelain Rock displays a porphyritic habit (Fig. 10). Here relatively large idiomorphic crystals of quartz and feldspar are enclosed in a fine textured crystalline groundmass of feldspar and quartz. The texture of this groundmass shows a marked idiomorphism of the lath-shaped feldspar. The feldspar constituting the groundmass seems to have in places a parallel arrangement, in others it occurs in felt-like aggregates.

This texture is exhibited in all the phases; even the most altered phases show this distinctive characteristic.

[5] Taylor, A. V.: Copper deposits of the world. XVI Int. Geol. Cong. Wash., D. C., 1932, p. 479.

Mineralogy and Mineral Habits.—In thin section the fresh phase of Porcelain Rock (Location N–3525–E–3520) seems to be composed of phenocrysts of quartz, orthoclase and basic plagioclase (not abundant) in a groundmass composed largely of quartz and orthoclase with a fair amount of acid plagioclase; microcline in small amounts was observed also.

The mineralogical composition of this rock has been calculated on the basis of thin section work as follows:

APPROXIMATE COMPOSITION OF THE FRESH PHASE OF THE PORCELAIN ROCK BASED ON THIN SECTION EXAMINATION AND RECALCULATED CHEMICAL ANALYSIS.

Quartz	30.0%
Orthoclase	30.0
Albite	32.0
Anorthite	5.0
Ferromagnesian minerals	2.7
Titanite	.3
Total	100.0

The more altered phases show that the mineralizing solutions have changed the character of these minerals, but as a whole the texture has been preserved.

All evidences cited—field, microscopic, mineralogic, and chemical—point toward the Porcelain Rock's being a rock of different origin from the granodiorite. Its porphyritic texture and occurrence points toward a rock of hypabyssal character. Its mineralogical composition points toward a rock very similar to the leucogranite described by Johannsen. However, its porphyritic habit makes it somewhat different. The writer is inclined to call this rock a leuco-granite porphyry.

The occurrence of fresh and altered phases of this rock in the ore body shows that the emplacement took place before sericitization and, therefore, before the introduction of sulphides. Its composition further indicates it to be an end phase of the differentiation of a granitic magma.

The alteration of the Porcelain Rock is entirely similar in nature to that observed in the granodiorite, but owing to the different compositions of the rock, the resulting material is somewhat different in appearance and mineralogical composition. As

far as observed, the process of decomposition has never been carried far enough to prevent the recognition of the prevailing characters. This may be due to the fact that this rock, where observed, has been located far from the source of mineralizing solutions.

SPECULAR HEMATITE AT CHUQUICAMATA

Specular hematite occurs in Chuquicamata along the Transition Zone. This mineral occurs in this zone as fine seams, stringers, and disseminations. As far as the writer is aware, the occurrence of this mineral is confined to this zone.

The study of a few thin sections of rocks of this zone shows that the specular hematite veinlets cut across the sericitized plagioclase, and in places these veinlets are accompanied by coarse sericite crystals. It seems from this relation, although it is not conclusively proved, that the specular hematite was formed during the sericitization period or somewhat later. It does not seem probable that it preceded the sericitation. None of the sections studied showed any sulphides, and, therefore, the age relation between the specular hematite and sulphide could not be established.

Referring to the age of this mineral, Taylor [5] says:

> The relation (between specular hematite and sulphides) have not been studied extensively, but the indications are that the hematite is hypogene and probably came in prior to the copper mineralization. That it is older than the copper mineralization is suggested by the fact that it exists mainly in the Transition Zone, where there has been little mineralization during the copper epoch; and as it also does not extend far into the unaltered granodiorite, it is believed to represent an introduction at the end of the early quartz period and to have been obliterated in other parts of the mine by the later mineralization. The only alternative possibility is that it represents an unusual low-temperature form marginal to the copper zone.

Specular hematite occurs in Chuquicamata in the minute tension fractures developed along the shear zone that forms the eastern boundary of the ore body. This zone, the Transition Rock, shows a strong development in chlorite minerals, and to

[5] Taylor, A. V.: Copper Deposits of the World. XVI Int. Geol. Cong., Washington, 1932, p. 479.

some extent has suffered some albitization. In the very border, outside of the chlorite zone, there is a large quantity of epidote. The association and occurrence suggest that the deposition of the specular hematite is genetically related to the above processes.

In the study of the rock alteration it was pointed out that the incoming solutions as they passed through the rock masses and travelled away from the source, changed in character from reducing to oxidizing. Chemically this means a reduction of much of the ferric iron of the original rock through which the solution travelled, and its removal toward the periphery where the solutions began to lose their reducing power. The appearance of epidote certainly shows that the solutions were not reducing by the time they reached this outer zone. The above suggestion does not preclude the idea that some or much of the iron was introduced with the solution, causing sericitization and removal of soda; it merely points out that by its own nature (reducing character), the iron could not be deposited along with sericite but had to be carried away toward the periphyry where the changes in character permitted its deposition. The above suggestion indicates only that the solutions, by the time they reached this zone, had lost their reducing action, but this does not necessarily imply that they were strongly oxidizing, otherwise we could not account for the presence of chlorite minerals.

SULPHIDE MINERALIZATION AT CHUQUICAMATA.

The study of the sulphide minerals occurring in Chuquicamata has been made and arranged in this paper in the order in which they occur in the present working of the deposit; that is from West to East—molybdenum and copper minerals.

The amount of molybdenum present in the deposit is very small. An analysis of the unweighted ore treated during the year 1927 shows 0.01 per cent molybdenum.[6]

The sulphides of copper have been arranged in the order of deposition, with first, description of the hypogene minerals, and second, those of supergene origin.

[6] Eichrodt, C. W.: The leaching plant at Chuquicamata, Chile. A. I. M. E., 91: 196–238.

No attempt has been made to bring out the relative economic importance of these minerals.

MOLYBDENUM MINERALIZATION.

One of the interesting features shown by the detailed geological mapping of the property has been the determination of the boundary of the rock containing molybdenum. The determination was brought about by the careful mapping of the areas in consideration and its comparison with the boundaries of high molybdenum content as determined by shovel-sample assay maps. The boundary was determined by the sampling, and coincides with the outer limit of the Sericitic Rock containing quartz lacing veinlets. The presence of molybdenum has been determined in either side of the Siliceous Rock, although not quantitatively in the western area.

A primary sulphide of molybdenum has not been found in the Siliceous Rock. It seems that the molybdenum present in this rock is of supergene origin in the form of lindgrenite or of molybdic ochres. It appears that the primary or hypogene molybdenum is confined to the quartz veinlets in the sericitic zone. However, a more thorough field study supplemented with examination in the laboratory will be necessary to substantiate this postulate.

Molybdenite (MoS_2) occurs in Chuquicamata as fine specks along the borders and as fine parallel bands in the margin and center of the quartz veinlets of the Sericitic Zone, adjacent to the highly silicified area. The occurrence of molybdenum as molybdenite is not common in the deposit at the present mining level. In most instances the molybdenite has been altered by supergene solutions to a red mineral that can easily be taken for limonite specks in the quartz veins. This new mineral is pseudomorphic after molybdenite.

The study of specimens of quartz veinlets from the Sericitic Zone brought out the discovery of this new mineral, which to the writer's knowledge has not been described to date. This mineral has a habit and occurrence similar to that of molybdenite in the

quartz veins, after the pyrite had been leached by supergene solutions. Closer study revealed that the red specks were really molybdenite pseudomorphs, some of the grains being six sided, and others of different orientations are elongated in the same fashion as the molybdenum sulphide. Under high magnification these minute crystals were found to be small aggregates of minute grains occupying the entire area of a former crystal of molybdenite, thus being a typical replacement structure.

In polished sections, the following characteristics were noted in the course of its study.

Under reflected light (non-polarized): color, light gray; hardness, 4 to 5; luster, sub-metallic.

Under polarized light: Mineral anisotropic, showing remarkably well the aggregate forms of the grains forming the internal structure of the crystal.

The following reactions were obtained when treated with a standard set of etching reagents:

HNO_3: Positive reaction. Fumes tarnish in spots from the drop. Mineral slightly etched. Internal structure brought out. Loses its luster and turns darker in color.

HCl: Positive reaction. Etches brown (rust-like) and deep. Reaction slow at first, becoming very rapid after being in contact with the reagent for a moment.

KCN: Positive reaction. Etches differently, bringing out the aggregate form of its internal structure, some of the grains of the aggregate being stained darker than others; this is probably due to the differential orientation of the grains in the aggregate.

KOH: Positive reaction. Reaction rapid, taking place as soon as the drop of the reagent comes in contact with the mineral. At the beginning the reagent acts differentially, attacking some of the grains of the aggregate sooner than others, but after a long contact the whole surface turns black.

FCl_3: Negative reaction.

HC_2: Negative reaction.

Microchemical tests made in minute samples, drilled from the grains show the presence of iron and molybdenum.

The writer believes the mineral to be a new species that has not been described and belonging to the molybdic ochre series. Its association with lindgrenite indicates that it is of supergene origin.

GENERAL CHARACTER OF THE SULPHIDE ORE.

The primary copper ore in Chuquicamata is found mostly in the veins in the vicinity of the pit, most of the ore in the pit being so thoroughly oxidized that samples of primary ores are scarce and only found now and then in the secondary sulphide zone in the Flooded area.

The primary ore obtained is a heavy, coarse to medium grained sulphide aggregate, in which enargite is the predominant sulphide of copper. In some of the specimens, enargite forms over 90 per cent of the mass, and in this case the specimen generally has a black color and metallic luster. In other specimens, pyrite is the predominant mineral, but it commonly appears as disseminated grains or in clusters in an enargite or chalcocite groundmass.

Enargite is, next to chalcocite, the most common sulphide mineral of copper. Bornite and chalcopyrite are always present but in such minute quantities as to be invisible in hand specimens.

Tennantite and some tetrahedrite are found in megascopic size in specimens from veins near the pit.

The gangue minerals are few, quartz predominating.

Mineralogy of the Copper Sulphide Veins.

The important sulphide copper minerals of Chuquicamata ores, named in the order of their relative abundance, are: chalcocite, enargite, covellite, tennantite-tetrahedrite, bornite and chalcopyrite. The gangue minerals are principally quartz and pyrite.

The order of deposition is somewhat different. The sequence in deposition is as follows: from hypogene solutions:

1. quartz
2. pyrite
3. enargite
4. chalcopyrite-bornite
5. tennantite-tetrahedrite

From supergene solutions, replacing hypogene sulphide:

1. chalcocite; 2. covellite

Primary Minerals (Hypogene).

Quartz-Pyrite.—Quartz seems to be the earliest mineral introduced along fractures. In most instances this early quartz is

shown in polished sections as euhedral grains. Quartz occurs as either isolated grains or in clusters with pyrite or enargite

The deposition of quartz took place probably through the entire sequence, so it is not rare to find quartz later than pyrite and enargite as secondary veinlets or as cementing material in a well brecciated enargite or pyrite mass. The early quartz appears as small, well formed crystals, as if deposition took place along open fractures, with plenty of space to allow the formation of perfect crystals. Later quartz appears in the form of interlocking grains as vein-filling material.

Pyrite is a common metallic mineral in the district. It is, next to the quartz, the most abundant constituent of the copper veins and of the altered granodiorite adjacent to the veins. It forms, with quartz, large quartz-pyrite veins, that have been later enriched by secondary chalcocite. Pyrite occurs also intermixed with all the metallic sulphides of the district. Under the microscope the pyrite of large aggregates appears as coarse interlocking grains, but isolated grains vary in size depending upon the amount of replacement suffered by later sulphides.

The facts regarding quartz-pyrite deposition may be summarized as follows:

1. Quartz is the earliest mineral introduced along open fractures. Its deposition continues through the main period of mineralization.
2. Pyrite deposition took place after the first quartz had crystallized in the existent channels. Pyrite occupies the open spaces and interstices existing along the quartz grains. Pyrite solutions had little chemical effect on the already crystallized quartz.

Enargite.—Enargite is the most abundant primary ore mineral of copper. It occurs in veins associated with pyrite and quartz in veinlets, and disseminated throughout the ore body. It is generally in interlocking grains of varying size but commonly medium grained, without crystalline outline, but with well developed cleavage.

Microscopically there are three well defined textural types of enargite, the coarse with grains up to 2 mm., the medium with grains up to 0.1 mm. and the finer size with grains below 0.01 mm. The coarse- and the medium-grained material occurs com-

monly in vein masses of different localities. The fine-grained variety has been observed around the margin of some larger grains, sometimes crossing them. The textural relations of the coarse grains to the fine seem to point to the origin of the latter as due to recrystallization along fractures developed in the larger grains right after consolidation, but while solutions containing enargite were still in circulation.

Enargite replaces pyrite more readily than quartz; in places the pyrite has been almost completely replaced by enargite.

The occurrence of enargite may be summarized as follows:

1. The solutions that deposited enargite followed along the same fracture zones used by quartz-pyrite. There is no evidences of major movements along this zone after the quartz and the pyrite had been crystallized.
2. Enargite replaces pyrite and some of the quartz.
3. Minor movements occur during the deposition and consolidation of enargite that cause fracturing of the large grains and granulation. Crystallization has afterward taken place along these fractures and granulation zones, while solutions containing enargite were still active, with the formation of stringers of fine grained enargite across the larger grains and around the granulated zones.

Chalcopyrite-Bornite.—The amount of chalcopyrite and bornite in the primary ores is quite negligible. They occur associated with pyrite and enargite in which they appear as small dots or gashes (Fig. 15). Their occurrence may be summarized as follows:

1. Chalcopyrite and bornite occur in minor quantities irregularly distributed in pyrite and enargite.
2. Chalcopyrite-bornite were in solution with the enargite, from which they were deposited contemporaneously with enargite.
3. Chalcocite replaces bornite more readily than it replaces chalcopyrite.

Tennantite-Tetrahedrite.—These minerals occur in the veins in the vicinity of the pit, but are sparse in the pit ore. It seems that the occurrence is confined to the veins in the outer N–E zone, bordering the pit.

Studies made of the specimens containing these two minerals reveal that the minerals called tennantite and tetrahedrite are really solid solutions of each other, in which tennantite probably forms the greater percentage. The solid solution of these two

minerals is light gray in color and appears light in contact with the pinkish enargite. It is definitely isotropic, whereas enargite is strongly anisotropic. The facts concerning the deposition of tennantite-tetrahedrite are summarized as follows:

1. Tennantite-tetrahedrite were introduced in the later stages of the mineralization, replacing enargite, chalcopyrite (Fig. 16).
2. Tennantite-tetrahedrite depositing solutions apparently were restricted to veins in the N E border of the mine.
3. Tennantite appears as small grains in the borders and boundary of tennantite-tetrahedrite grains with enargite; probably formed somewhat later than the solid solution of the two minerals.

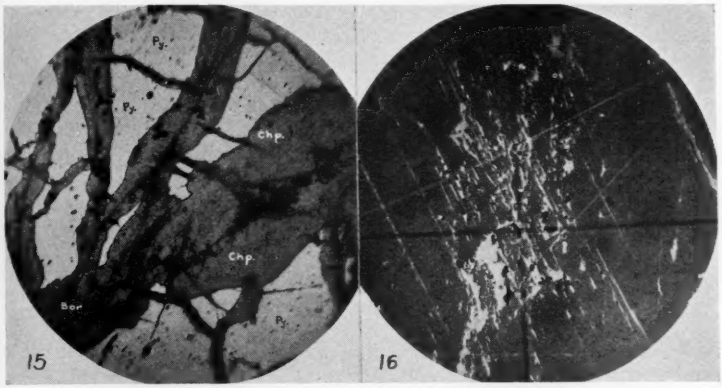


FIG. 15. Polished section showing chalcopyrite veinlets crossing pyrite, and being subsequently replaced by bornite. ×-nicols, × 160.

FIG. 16. Polished section showing replacement of enargite by tennantite-tetrahedrite along cleavage lines. ×-nicols, × 160.

Secondary Minerals (Supergene).

Chalcocite-Covellite.—Most of the chalcocite present in the samples examined seems to be of supergene origin. In all cases the chalcocite replaces all of the other sulphides and is in turn partly replaced by covellite.

In the study the writer could differentiate two types of chalcocite, both anisotropic, and, therefore, belonging to the orthorhombic system, the difference being in their etching patterns.

In one type the chalcocite after being etched with HNO_3 shows octahedral cleavage, and in the other type a pecular irregular parting was developed, like that of supergene chalcocite. Since the chalcocite is not isometric, the origin of the chalcocite with octahedral parting may or may not be hypogene. Relations show that chalcocite with octahedral parting occurs in close association with tennantite-tetrahedrite solid solution, replacing it, and may, therefore, be formed from hypogene mineralization as the last stage of deposition, when the temperature was somewhat higher than the inversion point.

There are not enough data to prove the formation of chalcocite from hypogene solutions, although such origin is strongly suggested.

Conclusions Regarding the Sulphide Mineralization.

The conclusions derived from the present study of the sulphide minerals are as follows:

1. Zonal distribution of the hypogene sulphide minerals, arranged in zones parallel to the highly siliceous core, and extending eastward as follows:

   a. Molybdenum zone, near the siliceous core in the sericitic and less silicified area, copper mineralization being weak. The molybdenum was introduced as molybdenite along the quartz veinlets, later being replaced by supergene solutions to an unidentified mineral thought to be a hydrous compound of iron and molybdenum which has not as yet been described.
   b. Zone of enargite, next to the sericitic zone, and strongest along the flooded area.
   c. Tennantite-tetrahedrite zone, appearing in the N–E border of the pit, associated with enargite veins.

2. Paragenesis of the hypogene copper sulphides are given below in their order of deposition:

   a. *Quartz,* earliest mineral formed. Its deposition was continuous during the formation of the copper sulphides.
   b. *Pyrite,* followed quartz.
   c. *Enargite,* followed pyrite. Forms the greater bulk of the hypogene copper minerals.
   d. *Chalcopyrite-bornite,* probably accompanying enargite solutions, which were deposited simultaneously with enargite.

e. Tennantite-tetrahedrite appears as solid solution replacing enargite. Tetrahedrite in small grains associated with tennantite-tetrahedrite solid solution.

f. Chalcocite. The bulk of the chalcocite has been formed by supergene solutions replacing all other sulphides. Chalcocite with octahedral cleavage may or may not be of hypogene origin. Lack of sufficient evidence makes its origin doubtful.

g. Covellite, of supergene origin, associated with and replacing chalcocite and other sulphides.

CARACAS, VENEZUELA,
April 1, 1939.

THE MONTAUBAN MINERALIZED ZONE, QUEBEC.[1]

F. FITZ OSBORNE.

ABSTRACT.

The mineralized zone in Grenville paragneisses has sphalerite, galena, chalcopyrite, and sulphides of iron with a gangue of skarn or cordierite and anthophyllite. The skarn is developed near and in limestone and passes by a series of transitional mineral associations into the cordierite-anthophyllite rocks developed in the absence of limestone. The structure of the limestones had an important role in determining the positions of the orebodies.

INTRODUCTION.

Location.—The Montauban mineralized zone near Montauban les Mines, Portneuf County, Quebec, is within a short distance from the edge of the pre-Cambrian rocks of the Grenville sub-province of the Canadian shield. The Tetreault mine, which has been the principal source of zinc and lead in this sub-province in Quebec, is on the south end of the zone. Zinc ore was discovered in the region in 1910, and development at depth accompanying exploitation disclosed an orebody trending north-south approximately half a mile long and extending from the first to the fifth level of the mine. During most of the period of operation the ore won had about 9 per cent zinc, 3 per cent lead, together with some copper, gold, and silver. During recent years the grade of the ore has been much lower than this. In all more than a million tons of ore have been mined from the Tetreault. The stopes in the mine are open giving the geologist a good opportunity to see the shape of the original orebody, and lateral exploration by cross-cuts makes it possible to determine the relationship of the orebody to neighboring formations.

Exploration of the ground to the north of the Tetreault orebody, which is characterized by a gangue of tremolite and diopside, as far as the Batiscan river failed to disclose an orebody

[1] Published with the permission of the Director, Quebec Bureau of Mines.

similar to that at Tetreault. The metasomatic zone showing some similarities to that surrounding the Tetreault body encouraged prospecting by pits, trenches, and shafts. A number of scientifically interesting occurrences of galena and chalcopyrite with some sphalerite in a gangue of anthophyllite and cordierite were found, but none has given evidence of being an orebody.

A detailed examination of the zone as a whole shows that the Tetreault ore-body with diopside and tremolite is in and near a body of limestone in the Grenville series, and that the cordierite-anthophyllite association is in paragneisses without limestone. Furthermore, it is possible to trace the one zone into the other through a series of transitional associations of gangue minerals. The structural relationships of the deposit are such that it is possible to discuss the genesis of the ore in greater detail than is usually the case.

Previous Work.—J. A. Bancroft made a geological map of the area to accompany his report published in the Quebec Bureau of Mines, Annual Report for 1915. According to his interpretation the mineralization is along a zone of tremolite derived from limestone of the Grenville series contained within Grenville paragneisses.

F. J. Alcock mapped the immediate vicinity of the Tetreault Mine for the Geological Survey in connection with the report on zinc and lead resources of Canada. He showed that the amphibolites are derived from basic igneous rocks which tended to form sills in the foliated rocks.

Various reports have been made for operators of the properties and some data for this paper have been taken from them.

GENERAL GEOLOGY.

The Montauban ore zone is along an overturned syncline of Grenville paragneisses and limestone that is surrounded by migmatites. The solutions that produced the gangue and ore rose along a sheared zone in the migmatites approximately the axial plane of the syncline.

Grenville Series.

The structural geology of the area surrounding the Tetreault has not been worked out in sufficient detail to enable the position of the deposits in the Grenville series to be determined accurately. However, some possibilities that become probabilities, in the light of analogies with the Grenville series elsewhere, will be outlined. East of Montreal the limestone members of the Grenville such as are characteristic in the type locality are not so thick as they are there. The succession at Shawinigan Falls, for example, shows an amphibolite formation, probably metavolcanic, underlying sillimanite and garnet gneisses which are succeeded upward by quartzites with limestones near the top of the series. A similar sequence has been observed in other regions in the Laurentian area. Amphibolites of a type similar to those at Shawinigan Falls occur ten miles east of Montauban. Quartzites are found between the mineralized zone and the amphibolites, whereas limestones nowhere occur in force within ten miles of the Tetreault. Amphibolites are found to the west of the mine. The principal Grenville rock type near the mineralized zone is sillimanite gneiss. These observations suggest that the ore zone is on the west limb of a syncline, and is in the lower part of the upper or meta-sedimentary phase of the Grenville. Relic structures indicate that the folding in this part of the Grenville was less tight than that in many regions.

Limestones are not ordinarily abundant in this part of the Grenville series, and the relative scarcity of limestone in the Montauban mineralized zone may be thus explained.

Grenville rocks other than those of carbonate are grouped together under the name of paragneisses and include quartzose biotite gneiss, sillimanite gneiss, garnet-sillimanite gneiss, and garnet-biotite gneiss. Table I shows the composition of some of these rocks. Most of the Grenville rocks have been so metasomatized that they have been converted to migmatites, but migmatization is less intense along the axis of a general synclinal structure coinciding in trend with the ore zone, and elsewhere enough Grenville persists that a picture of the original structure of the Grenville may be built up.

TABLE I.

	I.	II.	III.	IV.	V.	VI.	VII.	VIII.
Quartz	41.8	44.0	52.5	69.3	49.7	43.5	4.9	4.2
K Feld.	—	—	—	—	—	20.7	—	—
Plagioclase	31.8	26.0	19.5	18.7	30.4	28.7	52.2	22.7
Sericite	2.3	2.0	.2	1.0	1.6	.9	—	—
Sillimanite	—	4.0	18.0	—	—	—	—	—
Biotite	22.9	22.0	7.5	10.9	.5	5.9	3.9	—
Hornblende	—	—	—	—	16.2	—	37.2	54.9
Zoisite and Ep.	—	—	—	—	.6	—	.2	—
Chlorite	.1	.3	—	.1	.2	.1	—	—
Garnet	.7	1.5	—	—	—	—	—	16.2
Opaques	.4	.2	2.3	—	.2	.2	.4	1.5
Others	—	—	—	—	.6	—	1.2	.5

Mineral compositions in volume per cent—Averages of several specimens.
I, II, III, and IV—Various paragneisses.
V and VI—Representative migmatites.
VII—Amphibolite.
VIII—Garnetiferous selvage of amphibolite.

The foliation within the Grenville rocks is predominately of the bedding type, *i.e.* the schistosity is nearly if not quite parallel to the bedding. The folding as defined by bedding and schistosity is open except close to the axis of the syncline and may be considered of the competent pattern. Near the axis of the syncline particularly close to the carbonate an incompetent pattern with considerable overfolding becomes marked.

Viewed broadly the axis of the syncline is a zone of complex folding and is flanked by less deformed beds. The syncline pitches north, and a suggestion of its nose may be seen in the relic structures at the south end of the zone.

The general structural relationships require some explanation. The peculiarity of the structure is due to the fact that the amphibolites below the paragneisses are more resistant to deformation than the overlying formations. When the two were deformed together the more resistant formation tended to form broad arches[2] extending into the less resistant formation. The arches are separated by cusps (the synclines) projecting into the more resistant beds.

[2] Holmquist, P. J.: The relative plasticity of rock masses under the influence of dynamic deformation. Fennia, 50: No. 33, 1928.

Migmatites.—The migmatites are predominately fine-grained, grey gneisses of somewhat variable mineral composition. They have been called paragneisses by previous writers on the area but differ from paragneisses in that instead of a marked bedding schistosity, migmatites have a granitic aspect and a schistosity inclined to the bedding and schistosity of the replaced Grenville rocks. Injection and plutonic metasomatism along inclined *s* planes developed in the Granville rocks controlled the formation of the migmatites. Outside the main syncline, residuals of Grenville rocks that escaped migmatization do not show the inclined *s* planes megascopically. The rocks of the syncline do not show the *s* planes probably because they were cored with limestone too plastic to yield with the formation of the *s* planes.

The schistosity in the migmatites dips about 30° E. near the Tetreault. It steepens a short distance north, but the dip is less still farther north.

Amphibolite (sills) and Pegmatite.—Amphibolites (of the composition shown in Table I) derived from basic sills are found in the ore zone. They were emplaced in the *s* planes controlling the migmatization but were foliated by the stresses controlling the schistosity. The sills cut across the cordierite-anthophyllite zone, but they tended to nose or feather out against the diopside-tremolite zone. No amphibolite cuts across the main Tetreault ore zone, although sills extend into the ore zone from both sides. Apparently the rather plastic rocks acted as a brake on the advance of the sills where *s* planes were not developed.

The hill east of the principal workings of the Tetreault mine is capped by an opproximately horizontal tabular body of white pegmatite. The pegmatite is younger than the migmatization and amphibolites but as indicated by metasomatism of its edge next the ore zone is older than the ore.

Shear Zone.—The shear zone is approximately the axial plane of the synclinal mass. One drill hole cuts it below the level of the main orebody where it is in migmatites. It is there about 7 feet thick, sparsely mineralized with sphalerite and galena, and is sharply defined against the migmatites. It shows aligned crystals of mica with anthophyllite and what is probably pinite.

Within the limestone zone it is very irregular and tends to outline the blocks of diverse strength. It is particularly apparent along the " noses " of the amphibolites where they cut into the Tetreault zone. Within the paragneisses the shear tends to branch irregularly, but holds its general trend.

Although the shear zone was probably the channelway along which the solutions producing ore and the metasomatic zones rose, movements continued while the silicates of the metasomatic zone were forming.

It is the movement along this shear that is probably responsible for the pronounced slickensided surface forming the hanging wall of the ore zone 1,000 feet north of the main shaft.

GANGUE MINERALS.

The minerals produced by the metasomatism accompanying the introduction of sulphides, in contrast to those formed in the migmatites by what may be called " plutonic metasomatism," are of particular interest. In ensuing sections of this paper the various metasomatic zones are described and discussed. The mineral associations are such as have been described by Eskola and Tilley, but, for purposes of this paper, several associations are grouped to avoid complicating the discussion. The metasomatic silicates with the exception of brucite, chlorite (including leuchtenbergite), pinite, and probably hisingerite preceded the sulphides. Some of the carbonates, exclusive of those of the limestone, postdate the sulphides. Quartz is in minor amounts and both postdates and precedes galena.

The gangue minerals at the Tetreault are discussed separately from those in the cordierite-anthophyllite group.

TETREAULT MINE GANGUE MINERALS.

The solutions giving rise to the diopside-tremolite association came from depth and passed through the quartzose migmatites along fissures. Even in the migmatites they were rich in magnesia as indicated by the development of anthophyllite, cordierite, and mica in the sheared migmatites. In general the solutions did not affect the rock far to the sides of the shear planes. They

altered the paragneisses but the most noteworthy effects were in the crystalline limestones. The limestones are dolomitic but not dolomite: it could be debated whether the magnesia is original or the result of addition from solutions, either those associated with the ore, or those of an earlier metasomatism. The solutions probably carried some silica, silica was an impurity in the limestone; diopside was precipitated in the carbonate rock. It was apparently the paucity of silica that prevented the complete silication of the limestones at this stage. The solutions became enriched in lime and this lime was carried upward and to some degree laterally, and by reaction with the magnesia already in solution and the silica of the paragneisses, diopside was formed to replace the paragneiss. Tremolite was formed in the same loci somewhat later for some of the diopside is replaced by tremolite. However, most of the tremolite deposited without replacement of the diopside. In some places tremolitization of the carbonate rock was along shear surfaces and a linear arrangement of needles of tremolite is found. The surfaces may be the result of volume adjustment due to removal of lime from the carbonate. Tremolite was formed in the paragneisses in the same zone that contained the diopside. Most of it did not replace diopside but was probably the result of the addition of lime and magnesia to the rock containing available silica.

The relationships in the Tetreault body may be outlined as follows:

Magnesia was carried upward by solutions.
Lime was added to the solutions where the lime carbonate rock was encountered and the lime was carried upward and to a minor extent laterally in a region above the carbonates at depth.
Silica was present in the solutions but to only such an extent that a minor amount of diopside could form in the relatively pure carbonate, but in the siliceous paragneisses diopside formed abundantly.
Tremolite was stable after the diopside, and much of it was deposited independently of diopside. The formation of tremolite in the carbonate rock was probably the result of addition of silica and magnesia.

The above outline gives considerable importance to the rôle of silica. It is perhaps significant that quartz is not abundant even as a late stage mineral in the carbonate ore, but quartz veins occur in the tension cracks in the replaced paragneiss overlying the ore.

A consideration of the volume of carbonate rock and the diopside-tremolite skarn shows that the latter is much greater than the carbonate, and it is possible that there was more material abstracted from, than introduced into, the carbonate. It was suggested that some adjustment due to decrease in volume of the carbonate may have occurred. Until more data are available, this aspect of this problem must remain a matter for speculation.

CODIERITE-ANTHOPHYLLITE ASSOCIATION.

The cordierite-anthophyllite association is developed in the absence of lime from paragneisses some of which are rich in silica and others rich in alumina. All types of paragneisses are low in lime, and the magnesia content is not great. The first effect of the solutions on this zone seems to have been the conversion of the plagioclase about An 30 to plagioclase An 70 to 76. This conversion probably exhausted all the lime available in the rock. The tendency for alumina to combine with lime is shown elsewhere in the zone by the formation of metasomatic anorthite "anorthosite." The excess of alumina combined with silica and magnesia to form cordierite. Only a few armoured residuals of sillimanite occur in the zone. Staurolite can be found but is not abundant. Corundum and spinel are rare. Anthophyllite was probably coeval with tremolite. The low crystallizing force of cordierite as compared with the strong force of the amphibole makes the determination of relative ages uncertain. Furthermore, the common association of cordierite and anthophyllite in other regions may indicate that cordierite and anthophyllite are stable under the same conditions, and the possibility of overlap in the time of crystallization must be considered. Quartz is more abundant than in the diopside-tremolite zone.

There is little doubt that MgO was added to the metasomatic zone. The behavior of alumina is more uncertain. From the bulk composition of the various paragneisses it is certain the metasomatic zone has been enriched in alumina to give the abundance of cordierite and biotite, especially in view of the evidence that there has been little if any decrease in volume. The occurrence of large masses of cordierite shows that alumina was moved

appreciable distances. It would require accurate sampling of one bed and the metasomatic zone derived from it coupled with a determination of the volume relationships to determine the behavior of alumina.

The cordierite-anthophyllite association is found beneath the carbonate rocks in paragneisses on Tetreault property, but is separated from the tremolite-diopside rock by zones of different mineral associations. These zones are of minor importance and such as might be expected from phase-rule relationships in the system. Only one of the zones calls for particular comment and it is composed almost entirely of white anorthite (An 97). A few porphyroblasts of sphene are found. This zone occurs in the paragneisses and bounding the tremolite-diopside zone. It is relatively narrow and irregular and is the only mineral association indicating downward transfer of lime. The high percentage (36 per cent) of alumina in anorthite suggests that alumina was added. In places the anorthite has been converted to a pink or mauve aggregate of minerals. The material resembles wilsonite which is a derivative of scapolite in most of its occurrences but seems in places to have formed directly from anorthite.

The relationship of the cordierite-anthophyllite zone to the diopside-tremolite skarn zone of the Tetreault mine affords evidence of the character of the solutions that were probably under essentially the same pressure and temperature throughout the mineralized zone. It can be stated that MgO was added by the solutions in both zones. Lime was picked up from the limestone where it was encountered. Al_2O_3 was carried short distances at least by the solutions, but whether it was added in large amounts is uncertain. The solutions were not rich in SiO_2. The silication of the rocks was largely controlled by available silica. Even late stage quartz is not common in the skarn zones.

GENERAL AND THEORETICAL CONSIDERATIONS.

Although the Montauban deposits are the only ones of their type known in the Laurentian area in Quebec, certain of their features are similar to those shown in other places there. The problems they present are not, therefore, isolated ones, and must

be considered in the light of other occurrences in the region. An important problem is magnesia metasomatism, but it is not confined to the Montauban zone although it has various manifestations. In general these manifestations are confined to localities near one of the differentiates of the Morin series of igneous rocks.

Despite data to the contrary, it is difficult for the geologist who has worked in the Grenville sub-province in Canada to avoid the conclusion that magnesia has been added during metasomatism by solutions from acidic igneous rock; the occurrence of amphibolitized limestones on a regional scale and the deposits of magnesite and brucite along with serpentinized quartzites and sillimanite gneisses afford convincing evidence of the efficacy of magnesia metasomatism. The so-called metamorphic pyroxenites and related rocks are a varied group. Some of them are metasomatized para-rocks, others are contaminated granite pegmatites. In many places it is possible to trace a granite pegmatite into an aggregate of tremolite and diopside where limestones are intersected. In such rocks it is difficult to avoid the conclusion that magnesia was added by solutions from the pegmatite. It is obvious that the problem of magnesia metasomatism in the Laurentian region is beyond the scope of the present discussion. But for all the examples cited above, with the exception of some of the amphibolites, the source of much of the magnesia was differentiates of the Morin series. No other series in the region seems to have produced this effect so prominently.

A recent paper [3] by von Eckerman is significant in that in it he has outlined a course of differentiation of a stem not unlike the Morin, by which magnesia is concentrated into the rest solutions.

Morin rocks do not crop out in the vicinity of the Montauban zone, but a large batholith of the granite of the series occurs ten miles east of Montauban. Furthermore, apophyses of the same series cut the gray gneisses related to the migmatites at Cochon's quarry between Montauban and the edge of the batholith. It is reasonable to suspect, therefore, that the shear zone along the dejective Montauban fold reaches Morin rocks at depth. Simi-

[3] von Eckerman, H.: The anorthosite and kenningite of the Nordringrå-Rödö region. Geol. Foreign. Forh. 60, 4 b: 262–269, 1938.

larities of the rock alterations along the Montauban zone with those elsewhere is so great that it seems reasonable to ascribe the source of the ore solutions to Morin rocks. It is significant that every mineral occurring at Montauban with the exception of cordierite, staurolite, and gold has been found in the metamorphic pyroxenites and related rocks. It is easily possible that cordierite has been overlooked and staurolite has been called vesuvianite or garnet. The repetition of minerals throughout this group of metasomatic rocks is very striking and may be ascribed to the diversity of the composition of the rock replaced or through which solutions have passed, and the proportion of magmatic material. Certain rocks of this group are definitely of pegmatitic affinity consisting of quartz, microcline, biotite, zircon, apatite, and molybdenite with abundant scapolite, dolomite, diopside and tremolite. Phlogopite is abundant in some of these bodies. Others are replacement in limestone (normally high CaO varieties), quartzite, and sillimanite or garnet paragneisses.

Throughout the group the behavior of alumina is uncertain, for example at Kilmar, corundum and spinel occur where sillimanite gneisses have been replaced. The presence of large octahedra of spinel just as of large masses of cordierite argues that the alumina migrated to some extent, but it is difficult to prove that alumina was introduced in large amounts although in many places the assumption that Al_2O_3 was brought in is justifiable.

METALLIC MINERALS.

Twelve sections containing ore minerals from various parts of the ore zone were examined under the reflecting microscope. The surfaces confirmed the minerals megascopically identified but were not adequate to determine the sequence of minerals. Many more specimens would be required to work out the sequence, and the higher grade Tetreault orebody is so worked out it would be difficult to get characteristic specimens. Specimens could be got from pillars of lower grade ore or from the margins of the orebody but comparison of such specimens with some taken from dumps on the surface shows inconsistencies that are puzzling. The principal metallic minerals in the Tetreault ore are sphalerite,

galena, pyrrhotite, and chalcopyrite. Gray copper is fairly uniformly distributed in minor amounts, and stibnite, molybdenite, electrum, and arsenopyrite are of sporadic occurrence. Pyrite cannot be found in the high grade ore at the Tetreault. In some specimens pyrrhotite appears to have been replaced by sphalerite, chalcopyrite, galena, and gray copper, elsewhere sphalerite appears to be older than pyrrhotite (not cubanite with which pyrrhotite might be confused), chalcopyrite, and galena.

In the cordierite-anthophyllite rocks the same four sulphides appear, but galena and chalcopyrite are relatively more abundant than at the Tetreault. Pyrite is more abundant than at the Tetreault and it is almost as abundant as pyrrhotite. The pyrrhotite appears to have formed early, part of the pyrite replaces chalcopyrite parallel to its twin bands, but some of the pyrite is in porphyroblasts whose relationship to the other sulphides is indeterminate.

The occurrence of pyrrhotite as the sole sulphide of iron near the Tetreault ore-body, where the limestones originally occurred, in contrast to the presence of pyrrhotite and pyrite in the part of the zones where carbonate rocks were absent, is a point of interest. The normal sulphide in the Grenville limestones and in the metasomatic zones in them is pyrrhotite rather than pyrite, although pyrite occurs with pyrrhotite in the paragneisses and quartzites removed from limestone. These observations suggest that CO_2 formed by dissociation of the carbonates may have caused pyrrhotite to form instead of pyrite. It may be that some sulphide is converted to sulphate by the oxidizing action of CO_2. The mill operators have recorded the presence of a white dense mineral on the Wilfley tables treating Tetreault ore. This mineral is probably barite.

OTHER OCCURRENCES OF CORDIERITE AND ANTHOPHYLLITE.

Cordierite occurs in several associations and under diverse geological conditions. It is particularly widely developed in contact metamorphism of clay rocks and is found as a constituent of crystalline schists where shearing stress was deficient;[4] it

[4] Harker, A.: Metamorphism, Methuen, 1932, p. 231.

occurs in pyrogenic rocks that have crystallized in unusual fields due to contamination. Examination of the literature shows that cordierite-anthophyllite as a metasomatic mineral associated with mineral deposits is relatively rare. Nevertheless the examples described show some significant features and the occurrences throw some light on the genesis of the mineral association.

Most of and the best described of the examples are from the Baltic shield. Geologists of Finland, Sweden, and Norway have provided much data on the group and have been so impressed with the abundance of magnesium-bearing minerals that an extensive but as yet undecided controversy concerning the possibility and efficacy of magnesia metasomatism by solutions from acidic rocks has been carried on for many years in a series of papers.

It is unnecessary to summarize all the descriptions of occurrences in Finland and Sweden. Orijarvi [5] so adequately described by Eskola may be taken as an example of the class. The silicious leptites of Orijarvi are almost identical in character with the Grenville rocks termed paragneisses in this paper, indeed the Montauban paragneisses resemble the description of the leptites more closely than do most of the sillimanite or garnet gneiss of Quebec. Eskola's description of the cordierite-anthophyllite rocks might be applied to some of the Montauban rocks almost verbatim. Although the cordierite-anthophyllite rocks contain ore minerals, they do not constitute ores of any metal, but the ore is found in skarn rocks derived from limestones and dolomites associated with the leptites. This condition is found in many of the Swedish and Finnish occurrences and is so general it may be cited as almost a rule although cordierite may occur without anthophyllite as a gangue mineral of an oxide or sulphide ore in deposits in leptites.

The occurrence of cordierite and anthophyllite in the Peekskill emery deposits [6] at the contact of Manhattan schists and norite

[5] Eskola, Pentti: Petrology of the Orijarvi region. Bull. Comm. Geol. Finlande, No. 40, 1915, also No. 44, 1915.

[6] Gillson, J. L., and Kania, J.: Genesis of the emery deposits near Peekskill, N. Y., Econ. Geol., 25: 506–527, 1930, also 24: 182–194, 1929.

probably is to be related to the leptite type of deposits as is also the occurrence at Blue Hill, Maine. Other American occurrences are of petrologic rather than economic interest.

Cordierite and anthophyllite are developed by metasomatism in greenstones, meta-andesites and meta-basalts. A number of such occurrences have been described as petrologic curiosities; Botallack, Cornwall,[7] was the subject of a paper by Tilley and Flett and one by Tilley, and is particularly interesting in that Tilley deprecated the possibility of magnesia metasomatism but later admitted that there had been an "internal magnesia metasomatism" under the influence of emanations from granite.

Cordierite and anthophyllite are extensively developed from greenstones near rhyolites close to the large deposit of sphalerite, chalcopyrite, pyrite, and pyrrhotite at the Amulet mine, Quebec.[8] Mica, chlorite, gahnite, and quartz are associated with the other gangue minerals. The anthophyllite has a birefringence a trifle lower than usual. Some thin sections from the Waite-Ackerman-Montgomery Mine, Quebec, show anthophyllite associated with sphalerite; the dominant amphibole of the deposit is, however, tremolite. No cordierite can be identified in the thin sections, but areas of scaly alteration product in the anthophyllite-bearing rocks may be pinite derived from cordierite.

An occurrence of pyrite, pyrrhotite, and chalcopyrite replacing andesites and dacites at Gull Lake, Newfoundland, was described in an unpublished thesis by A. C. Bray whose thin sections are in the petrographic collection at McGill University. The gangue minerals are cordierite, anthophyllite (described as tremolite by Bray), biotite, chlorite, quartz, and sericite. A rim of chlorite invariably separates sulphides from cordierite. The rocks resemble those from Amulet, but cordierite is less abundant than it is there.

The Montauban mineral deposits show the greatest similarity to the cordierite-anthophyllite and skarn deposits in the leptites and carbonate rocks of the Baltic region and are different in mode of

[7] Tilley, C. E., and Flett, J. A.: Summ., Rept. of Prog. Geol. Surv. Gt. Britain, Pt. 2, 1930 for 1929, pp. 24–41. Tilley: Mineral. Mag., 24: 181–202, 1937.

[8] Wilson, M. E.: Rock alteration at the Amulet mine, Noranda district, Quebec. ECON. GEOL., 30: 478–492, 1935.

occurrence from the deposits in Abitibi related to the greenstones. The Montauban occurrences are unlike the occurrences of lead and zinc ores in Grenville limestone at Calumet island, Quebec, and Balmat and Edwards, New York, but part of the skarn body at the Tetreault shows a greater resemblance, at least as regards minerals, to the deposits mentioned.

The rigorous conditions obtaining in at least the early stages of the metasomatism is clearly recorded by the gangue minerals. The Montauban deposits might be classed as hypothermal; whether it is desirable to refer to the Tetreault ore-body or the whole zone as pyrometasomatic is less certain. The tendency to restrict the term pyrometasomatic to replacement in limestone raises the question of whether the skarn segment of the zone where limestones occur should be classified differently from the cordierite-anthophyllite-bearing segment devoid of limestones. Such a division seems illogical and, unless the term pyrometasomatic can be applied to gangue association antipathetic to limestone, the term hypothermal is adequate.

The Montauban mineralized zone throws some light on the problem of magnesia metasomatism. The geologist with experience in the Grenville area in Quebec can hardly escape the conclusion that magnesia was transferred from rocks of the Morin series. The peculiar relationships at Montauban show clearly the role of magnesia introduced into limestone in forming skarn rocks, and indicate the importance of the composition of the wall rocks on the character of the gangue minerals formed in this type of deposit.

The control exercised by the structure and physical characteristics of the country rocks is significant. The ore-forming solutions passed through the migmatites but did not affect them except along the shear zone. The amphibolites were equally resistant to replacement. The paragneisses and the limestone were drastically altered by the solutions. The carbonates were especially favorable for replacement by ore minerals.

McGill University,
Montreal, Quebec,
May 14, 1939.

DISCUSSION AND COMMUNICATIONS

DISLOCATED INCLUSIONS IN VEINS.

Sir: The interesting article by Mr. Rollin Farmin on "Dislocated Inclusions in Gold-Quartz Veins at Grass Valley, California," in the September-October, 1938, issue, raises some questions in my mind that probably others besides myself would like to have answered.

Let me make it clear at the beginning that I have not specialized in geology and have not kept notes on the geological details of veins I have seen and so cannot cite specific examples to support the points I am about to mention, but I have seen a large number of veins in the course of many years of experience and I feel sure many other mining men and geologists will have observed cases in point.

Although the following remarks are based on features observed in tertiary silver-gold and silver-gold-lead-zinc veins, rather than in gold-quartz veins, the principles involved probably apply to dislocated inclusions in veins generally.

The hypothesis of "ore magmas," "concentrated magmatic solutions," or other solutions of specific gravity high enough to support fragments of wall rock seems to me to give rise to the following questions:

1. Fragments so supported must be assumed to be formed when the fracture is opened and therefore to be carried along with the current until movement ceases. This implies transportation for considerable distances from the places of origin. How does it happen, then, that such fragments are so often only slightly removed from others, or from irregularities in the wall, into which they would fit?

2. How is it that fragments so often show signs of shattering, such as tiny veinlets through and across them, if the intrusion of

the magma of solution were relatively quiet, as I should think it would be under such a hypothesis?

3. Does it explain satisfactorily the occurrence in a massive vein, of included fragments of similar vein matter that may make up as much as 50 per cent or more of the vein?

4. How does it happen that the alteration of included wall rock fragments is often so even throughout the whole of the fragment, as if caused by thorough permeation such as might take place over a considerable length of time? Surely assimilation by a dike-like fluid would tend to show more definite evidence of progressive alteration from the outside towards the center, if it took place at all.

5. Would this hypothesis account for the varying degrees of alteration of fragments of the same rock, varying from practically unaltered fragments to the merest ghosts, regardless of size, in close proximity?

6. Would it explain the quite local areas in some veins where the included fragments of wall rock make up more than 50 per cent of the mass and give the impression of a mineralized breccia?

Others no doubt could add more questions of a similar nature, raised by features that appear inconsistent with the hypothesis.

It is much easier to question the soundness of the conclusions drawn by Mr. Farmin and other writers, all of whom deserve credit for contributing to the solution of a question that has puzzled so many, than to offer an alternative explanation, and it is hardly fair to criticize without making some attempt to submit some such alternative. With this feeling in mind I suggest the possibility of surges of *thin* solutions, that might at times possibly attain explosive violence, due to obstructions and their overcoming, as by breaking through a dam behind which pressure builds up gradually. Being thin, and, therefore, of specific gravity much lower than the wall rock, such solutions when impounded would in their lower reaches have pressures similar to the rock pressure at that place, whereas higher up the pressure in the liquid would be less by the weight of the liquid in the column, but the rock pressure at the higher elevation would be lower by a considerably greater amount due to the higher specific gravity of

the rock, thus at higher horizons there would result greater pressure in the liquid than in the adjacent rock.

It would follow that if the supply of solution from below were sufficient, the preponderance of the liquid pressure over the rock pressure would increase with the elevation until it found sufficient release to take care of all the excess solution available. The presence of volatile constituents in the solution would tend to increase the violence of release. If the supply of solution were great enough, at least a part would reach the surface. Even with small supplies such would tend to be the case owing to the squeezing resulting from rock pressure, although the pressure of the rock against the liquid would be reduced after the latter had an outlet, due to its being taken up in part by stresses within the rock.

Should the course of the liquid be dammed, its pressure would accumulate until it broke through the obstruction, if sufficient liquid were available from below. Such conditions might occur at almost any depth. Rock pressure alone might produce them in great depth. Sealing of a channel by a vein during a period of quiescence might cause them at higher elevations, although the channel so sealed might still be weaker than the country rock. Movement along a vein fracture would tend to maintain it as a plane of weakness, as would any softening of the walls along it. These two latter conditions would mitigate against violent surges and veins forming in pre-existing fractures of this kind would not be characterized so much by included fragments as by banding.

The question arises how surges might affect the deposition of ore minerals. Relatively sudden release from pressure would tend to cause general precipitation of all minerals whose solubilities were reduced sufficiently by it to create super saturation. Such precipitates would be very fine, perhaps even colloidal in some cases, and fairly homogeneous mixtures. If the activity of particles be proportional to their surface: mass ratio, would not the urge toward stability tend to result in gradual segregation and rearrangement with the building up of larger crystals? Does not limestone crystallize after deposition and do not chert and flint nodules build up in some such way? Would not this be a possible

explanation of the juxtaposition of minerals having different solubilities?

In sections of the fissure that remained open after a surge, during the period of quiescence that might follow, crustification on the walls and exposed surfaces could take place.

The introduction of the possibility of segregation and rearrangement of the minerals, with the growth of crystals as a result, brings up another question that has bothered me, namely:

Geologists the world over utilize the interrelation of crystal boundaries to determine the age relations of deposition and often draw from it conclusions of changes in the composition of the mineralizing solutions. If, however, the crystal boundaries of vein minerals were the result of segregation and recrystallization or, crystallization after original deposition in colloidal form, the conclusions regarding age and changing nature of the solutions would be false. To carry this idea still further, a change in conditions after a deposit has formed—in pressure and temperature as a result of erosion, rock stresses and movements, intrusions and extrusions (producing a blanketing effect) or in the composition of the groundwater such as in dispersing agents, coagulators, flocculators, electrolites, catalysers or other contents —might change stability conditions so as to result in a re-arrangement of some minerals.

In view of these possibilities, how much reliance can be placed upon age relations so determined or upon supposed changes in the nature of the mineralizing solutions deduced therefrom?

C. B. E. DOUGLAS.

PACHUCA, MEXICO,
May 24, 1939.

REVIEWS

Geology and Ore Deposits of the Lordsburg Mining District, New Mexico. By SAMUEL G. LASKY. Pp. 62; Pl. 25; figs. 9. U. S. Geological Survey Bull. 885. Prepared in cooperation with the State Bureau of Mines and Mineral Resources, New Mexico School of Mines, 1938. Price, $1.25.

A study of the Lordsburg mining district, New Mexico, was undertaken jointly by the U. S. Geological Survey and the New Mexico Bureau of Mines and Mineral Recources. The work has been done in less detail than originally planned due to the fact that the mines were largely closed down in 1932 as a result of the depression, with but little hope that activity would be resumed in the future. Operations in the district were chiefly due to an unusual demand for siliceous fluxing material at the nearby copper smelter, rather than for the metallic content of the ores. A large proportion of the ore came from the Eighty-five mine and, with the exception of a few small properties mining moderately enriched ore, most of the operations have been based on low-grade hypogene ores. According to the author, the future of the district would continue to depend on the demand for fluxing ore.

A detailed abstract of the contents of the bulletin is followed by a short introduction covering the scope of the present work and a bibliography of publications referring to the Lordsburg district. The bibliography includes four articles by Dr. Lasky in which certain aspects of the area are treated in somewhat greater detail than in the present report. The remainder of the bulletin is devoted to a discussion of the general geology of the area, the ore deposits and the individual mines. The bulletin is well illustrated with geologic maps, sections, isometric diagrams, sketch maps, photographs, photomicrographs and mine maps.

The most important rock unit of the district, particularly as regards mineralization, is an irregular, porphyritic granodiorite stock of either late Cretaceous or early Tertiary age. This has intruded basalt flows of Comanche (Lower Cretaceous) age and basaltic and rhyolitic rocks which are younger than the Comanche rocks. Later, plugs and dikes of quartz latite and dikes of white felsite were intruded and, after a long period of erosion, Miocene (?) lavas and associated breccias and tuffs were deposited.

Faulting began shortly after the intrusion of the granodiorite stock and ore was deposited in the fault fissures. The faults trend eastward and northeastward and are confined largely to zones that follow the general outline of the stock. At least seven stages of movement, with six distinct stages of mineralization, are recognized by the author. Only the second stage of mineralization resulted in exploitable ore deposits.

The ores of the Lordsburg district belong to the copper-tourmaline type and they are one of the few known examples of this type in the United States. Deposition of vein filling took place during faulting with material of a different character being deposited with each reopening of the fissures. The vein filling consists of vuggy and drusy masses and, except possibly during the first stage, the openings were never completely filled.

The Emerald vein, on which the Eighty-five mine is located, has been mined continuously to a vertical depth of 1,900 feet and has produced 1,500,000 tons of ore with an average of 2.80 per cent copper, 1.23 ounces silver and 0.111 ounce gold per ton.

Supergene alteration of the ores is erratic. Gold and copper ores have been enriched in some places and impoverished by leaching in others. The average silver content, however, is judged to have been increased by supergene enrichment.

PHILIP KRIEGER.

The Nature and Origin of Coal and Coal Seams. By A. RAISTRICK AND C. E. MARSHALL. I–VII, 13–282. The English Universities Press Ltd., 1939. Price 12/6.

This text book appropriately dedicated to the memory of two "pioneers in the study of coal and coal seams" Percy Fry Kendall, F.R.S., and Reinhardt Thiessen will find a place in the library of everyone interested in the origin, occurrence, classification, and the mining of coal. It is primarily designed as a geologic interpretation of the "problems and phenomena encountered by those who have practical concern with the getting and using of coal." It undoubtedly takes a place now as the foremost book on the subject in the English language.

The authors discuss in the first 8 chapters the strata of the Coal Measures, the coal beds and associated strata, the origin of coal as a peat deposit, splitting of coal beds, irregularities in coal beds due to erosion and faulting, correlation methods and the economic products of the Coal Measures—ganister, sandstones, clays and shales, oil, and coal. In Chap. 9 the coal flora are described briefly. The discussion of coal petrology, Chap. 10, is concerned with the general features of the microscopic paleobotany of coal, particularly of the bright coal. In Chap. 11 the chemical constitution of coal is discussed, particularly the proximate form of analysis, and the variations in this form analysis due to variations

in coal type. Thus far the book deals almost entirely with the British Coal Measures and British coals. Chap. 12 in which is discussed coal rank, gives considerable space to American as well as to British coals. The final chapter, 13, concerns the igneous alteration of coal beds, particularly contact metamorphism, whereby the coal bed is either entirely incinerated or is altered to coke.

The first nine chapters are primarily of local interest since they give special attention to conditions within the British coal fields. The discussions of the nature of the associated rocks with their local names provides a basis for comparison with conditions in the American coal fields. Worthy of special note is the reference to cyclical sedimentation, which the authors state is particularly characteristic of the Westphalian (Yorkian) Measures. The sequence differs from that observed in the Illinois basin, as described by Wanless and Weller, mainly in the general absence of marine beds, particularly limestones above the coal, although occasional marine beds are found at this position. The nodular earthy limestones commonly found at the base of the underclays in the Coal Measures of the Illinois basin are likewise absent in the British Coal Measures. Raistrick and Marshall start the cyclical formations with the coal beds, although sandstones, locally unconformable at the base, are present within the sequence just as they are in the Illinois formations.

Many of the phenomena of "washouts" have their counterparts in the "cutouts" of the American coal fields.

The discussion of coal petrology introduces a new interpretation of clarain as bright coal, and, what seems to the present reviewer, an unfortunate substitution of the term vitrinite for vitrain. Clarain is referred to as a type of coal, but vitrain, or vitrinite is not so regarded, apparently because clarain almost always contains more or less vitrain in thin bands. Why a thick band of vitrain an inch to three inches in thickness should not be regarded as much a type of coal as adjacent clarain is not clear.

It is said in Chapter X, p. 196, that cannel coal does not contain substantial amounts of micronite (opaque matter); yet the transition from cannel coal to durain is said to be perfect. Should such transitional coal be called cannel coal or splint coal—assuming that splint coal and durain are the same? It is the writer's experience that certain cannel coals, that is coals having the megascopic appearance of cannels, not uncommonly contain considerable amounts of opaque matter. On the other hand there are other cannels, having the same general megascopic appearance, that are translucent, in other words there are both partially opaque and translucent cannels.

The discussion of type variation of coals apparently sets forth the American point of view in regard to meaning of type. It is a distinct

contribution toward the solution of the coal classification problem. In connection with this discussion the authors have done well to call attention to the contributions of Professor Hickling in the interpretation of type variations.

In the discussion of the chemistry of coal it is to be regretted that no consideration was given to the mineral-matter-free basis of comparison, since this is undoubtedly logically more defensible than the ash-free basis.

GILBERT H. CADY.

URBANA, ILL.,
June 5, 1939.

Our Natural Resources and Their Conservation. 2nd. Edition. Edited by A. E. PARKINS AND J. R. WHITAKER. Pp. 647; illustrated. John Wiley and Sons, New York, 1939. Price, $4.00.

This edition following only three years after the first edition, has permitted elimination of early duplication because of the large number of contributors (23); it also permitted cross references, which were lacking before. The same general plan has been followed, namely ten parts dealing with conservation of land and soils, forests, water supply, mineral resources, wild life and fisheries, recreational resources, conservation of man, and political features. In the short interval not much new material could be added and the chief changes are coordination with minor additional material.

Descriptive List of the New Minerals, 1892–1938. Compiled by G. L. ENGLISH. Pp. 258. McGraw-Hill Book Co., New York, 1939. Price, $3.00.

This convenient volume contains all new mineral names since the 6th edition of Dana's "System of Mineralogy." However, it does include those given in the three appendices to the 6th edition and in the 4th edition of Dana's "Textbook of Mineralogy." Under each mineral name is given the references to original publication, references to abstracts and where available, descriptions, occurrence, properties, localities, and cross names.

It is a time saving book for all who wish to look up minerals.

A Textbook of Geomorphology. By P. G. WORCESTER. Pp. 565; figs. 375. D. Van Nostrand Co., New York, 1939. Price, $4.00.

This book is planned for an introductory course requiring little or no previous knowledge of geology, and represents work covered by the author's course at the University of Colorado.

The 16 chapters cover Relief of the Earth; Earth and Sun; Materials of the Lithosphere; Earth Movement and Structure; Weathering; Topography produced by streams of humid and semi-arid regions, by glaciers and groundwater; Lakes and Swamps; Shore Forms and Processes; Volcanoes; Islands and Coral Reefs; Plains, Plateaus and Mountains. It is clearly written and well illustrated with good maps, drawings and photographs, many of them aerial. It is nicely printed on a good surfaced paper. It should prove an excellent book for an elementary course.

BOOKS RECEIVED.

J. D. BATEMAN.

The Diamond Industry in 1938. SYDNEY H. BALL. Pp. 16. Jewelers' Circular-Keystone, New York, 1939. *A detailed and authoritative booklet with production, consumption, sales, prices and diamond notes.*

Geological Map of Missouri. 42½″ × 48½″; scale, 6⅜″ = 50 miles; colored. Missouri Geol. Surv., Rolla, 1939.

Geophysical Abstracts 94, July–September, 1938. W. AYVAZOGLOU. Pp. 45. U. S. Geol. Surv. Bull. 909–C, Washington, 1939. Price, 10 cts.

Nickel Content of an Alaskan Basic Rock. JOHN C. REED. Pp. 5; fig. U. S. Geol. Surv. Bull. 897–D, Washington, 1939. Price, 5 cts. *Comparison of petrographic measurements and chemical analyses.*

Some Linguloid Shells From the Late Devonian and Early Carboniferous Rocks of Pennsylvania and Ohio. GEORGE H. GIRTY. Pp. 20; pl. U. S. Geol. Surv. Prof. Pap. 193–C, Washington, 1939. Price, 10 cts. *Systematic descriptions of twelve species.*

Notes on Fossils from the Eocene of the Gulf Province. JULIA GARDNER. Pp. 27; figs. 6; pls. 3. U. S. Geol. Surv. Prof. Pap. 193–B, Washington, 1939. Price, 10 cts. *Twelve new species included.*

A Monograph of the Foraminiferal Family Monionidae. JOSEPH A. CUSHMAN. Pp. 100; pls. 20. U. S. Geol. Surv. Prof. Pap. 191, Washington, 1939. Price, 30 cts. *Systematic descriptions.*

The Geology of Leon County, Texas. H. B. STENZEL. Pp. 295; figs. 61; pl. Univ. of Texas Pub. 3818, Austin, 1938. Price, $1.00. *Stratigraphy, physiography, structure and economic geology of the district.*

Geophysical Report on the Croydon-Golden Gate Area, Croydon Gold and Mineral Field. J. M. RAYNER AND P. B. NYE. Pp. 27; figs. 2; maps 6. Aerial, Geol. and Geophysical Survey N. Australia, Queensland, Rept. 9, Canberra, 1939. *Electromagnetic surveys of an important gold producing area.*

Geology and Mineral Deposits of the Baie D'Espoir Area. W. B. JEWELL. Pp. 26; figs. 12; geol. map. Newfoundland Geol. Surv. Bull. 17, St. Johns, 1939. *Physiography, petrography, structural and economic geology.*

Surface Water Supply of the U. S., 1937. Part 3, Ohio River Basin. N. C. GROVER ET AL. Pp. 375; pl. U. S. Geol. Surv. W. S. P. 823, Washington, 1939. Price, 40 cts.

Floods in the Canadian and Pecos River Basins of New Mexico, May and June, 1937. TATE DALRYMPLE ET AL. Pp. 68; figs. 7; pls. 9. U. S. Geol. Surv. W. S. P. 842, Washington, 1939. Price, 20 cts.

Major Texas Floods of 1935. TATE DALRYMPLE ET AL. Pp. 67; figs. 10; pls. 9. U. S. Geol. Surv. W. S. P. 796–G, Washington, 1939. Price, 15 cts.

Geology and Mineral Deposits of the Canada Bay Area, Northern Newfoundland. FREDERICK BETZ, JR. Pp. 53; figs. 12; pls. 7. Newfoundland Geol. Surv. Bull. 16, St. Johns, 1939. *Possible commercial marble deposits.*

Geological Map Alberta. JOHN A. ALLAN. 16⅛″ × 27⅞″; scale, 1½″ = 48 miles; black and white. Alberta Geol. Surv. Research Council, Edmonton, 1939.

Annuaire, 1938–1939. Bur. D'Etudes Geol. et Min. Coloniales. Pp. 631. Paris, 1939. *Bibliography of publications; statistics; alphabetical lists of societies.*

Magnesium, Magnesite and Dolomite. J. LUMSDEN. Pp. 126. Imp. Inst. Min. Resources Dept., London, 1939. Price, 2/6. *Special emphasis on Empire deposits but reviews world resources. Good bibliography listed by countries.*

Ground-water Resources of the Holbrook Region, Arizona. M. A. HARRELL AND E. B. ECKEL. Pp. 85; fig., pls. 8; maps 2. U. S. Geol. Surv. W. S. P. 836–B, 1939. Price, 50 cts.

Floods of Ohio and Mississippi Rivers, January–February, 1937. Pp. 746; figs. 97; pls. 25. U. S. Geol. Surv. W. S. P. 838, 1938. Price, $1.25. *Floods caused by a succession of heavy rain storms.*

Oil and Gas Exploration Map, Labette County, Kansas. G. E. ABERNATHY. Kan. Geol. Surv., Lawrence, 1939.

Quelques remarques sur les Mines metalliques Tropicales et en particulier sur les Mines d'Or. R. SAUZE. Une méthode nouvelle en Métallurgie aurifère L'amalgamation sous pression par utilisation de la tension superficielle. G. Passelecq. Pp. 33; figs. 4. Bur. d'Études Géol. et Min. Coloniales, Pub. No. 13, Paris, 1939.

Report on Aranka Goldfield, Cuyuni River. D. A. BRYN DAVIES. Pp. 25; figs. 2; pls. 3. Geol. Surv. British Guiana Bull. 10, Georgetown, Demerrara, 1939. Price, 24 cts. *Alluvial, eluvial and residual deposits. Considerable production by hand methods; possibility for small plant.*

Preliminary Report on Geology and Gold Occurrences of the Kahama Region. D. R. GRATHAM AND B. N. TEMPERLEY. Pp. 14; map. Geol. Div. Dept. Lands and Mines, Tanganyika Territory, Short Paper 21, Dar es Salaam, 1939. Price, 2/–. *Two zones of economic interest.*

SCIENTIFIC NOTES AND NEWS

H. C. GUNNING of the Bureau of Geology and Topography, Department of Mines and Resources, Ottawa, has been appointed professor of geology at the University of British Columbia in Vancouver.

E. N. PENNEBAKER, chief geologist of Consolidated Coppermines Corp., returned to Kimberly, Nevada, in July after several months in Cuba.

IRA B. JORALEMON and his associates of San Francisco, who have been prospecting and developing the Dan Tucker mine near Fallon, Nevada, are exercising their option to purchase.

CLAUDE E. NEEDHAM has been selected president of the New Mexico School of Mines to succeed Edgar Herbert Wells, deceased.

EDGAR BOWLES, staff geologist for the Alabama State Geological Survey, received the degree of Doctor of Philosophy from the Johns Hopkins University department of geology last June.

H. FOSTER BAIN left June 14 for Europe on his way to Manila.

M. G. HEARN of the department of geology at the University of the Witwatersrand, Johannesburg, S. Africa, is visiting the mining districts of the United States and Canada for six months.

GEOFFREY GILBERT of Toronto is now in Trail, B. C., as geologist for Consolidated Mining and Smelting Co.

GUY N. BJORGE, general manager of the Homestake Mining Co., received an honorary degree of Doctor of Engineering last June from the South Dakota School of Mines.

G. M. FURNIVAL has resigned from Cline Lake Gold Mines, Ltd. to become assistant geologist with the Geological Survey of Canada at Ottawa.

PHIL B. DOLMAN has leased and will operate the former Oyler Lode property at Bear Valley, California.

O. H. METZGER, mining engineer of the U. S. Bureau of Mines, has recently been examining a number of chrome properties in the district south of Canyon City, Oregon.

J. A. TITCOMB is now with the Newmont Mining Corp. in New York City.

P. E. FAIRBAIRN has returned to London after resigning as assistant geologist for Trepca Mines, Ltd. in Jugoslavia.

B. H. PARKER is on a year's leave of absence from the Colorado School of Mines to carry on geological investigations for the Argentine government.

A. M. GAUDIN, professor of mineral dressing at the Montana School of Mines for the past ten years, has been appointed Richards professor of mineral dressing at Massachusetts Institute of Technology.

L. K. WILSON, assistant geologist for the Cord Nevada mining interests at Silverpeak, Nev., has recently been made geologist.

EDWARD WISSER has recently been engaged in professional work in the vicinity of Auburn, California.

M. D. GARRETTY has been appointed chief geologist of North Broken Hill, Ltd., Broken Hill, N. S. W.

ALAN M. BATEMAN, Professor of Economic Geology at Yale University, spent some time during the summer at the Utah Copper Co., Bingham, Utah, the Nevada Consolidated Copper Co., Ely, Nevada, the Ray Mines, Ray, Arizona, and the Chino Mine at Santa Rita, New Mexico.

The twenty-fifth annual meeting of the AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS will be held at the Stevens Hotel, Chicago, Illinois, on April 10, 11, 12, 1940, at the invitation of and sponsorship by the Illinois Geological Society.

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